LV ENGINE

Close Down Report

Contents

Disclaimer

This is the close-down report of project LV Engine, a globally innovative project to demonstrate the functionalities of a Smart Transformer, funded by Ofgem through the Network Innovation Competition mechanism. All learnings, outcomes, models, findings information, methodologies or processes described in this report have been presented on the information available to the project team at the time of publishing. It is at the discernment and risk of the reader to rely upon any learnings outcomes, findings, information, methodologies or processes described in this report.

Neither SPEN, nor any person acting on its behalf, makes any warranty, representation, undertaking or assurance express or implied, with respect to the use of any learnings, outcomes, models, information, method or process disclosed in this document or that such use may not infringe the rights of any third party. No responsibility or liability is or will be accepted by SPEN, or any person acting on its behalf, including but not limited to any liabilities with respect to the use of, or for damage resulting in any way from the use of, any learnings, outcomes, models, information, apparatus, method or process disclosed in the document.

Executive Summary

Background problem

The UK government's intention to electrify the transportation and heating sectors will result in an increase in network demand despite improvements in energy efficiency. The growing connection of Distributed Generation (DG) is also causing an additional strain on the Low Voltage (LV) network. Conventional network reinforcement, which can be prohibitively expensive, disruptive and time consuming, may not represent best value for money for our electricity customers. Some network issues such as voltage rise, voltage drop and thermal stress on assets are expected to increase significantly while more customers rely on the electricity network for their heat and transport demand or local generation. Conventionally, LV networks are passive and designed for the worst demand and generation conditions with limited flexibility to allow for uncertainties around where, when and what level Low Carbon Technologies (LCTs) will be connected.

To overcome the aforementioned challenges, LV networks need to be more flexible, controllable and active. Secondary substations, as the bridge between LV and the rest of grid, can be intelligent hubs providing smart functionalities and the flexibility required for the operation of our future LV networks.

LV Engine Method

LV Engine aims to add flexibility and release additional network capacity within LV networks, by introducing an intelligent secondary transformer solution by designing and trialling the first UK Solid State Transformer (SST) for deploying within secondary substations (11kV/0.4kV). SSTs provide multiple functionalities which can bring value to the LV network. However, LV Engine will focus and demonstrate the following preliminary smart SST Core Functionalities under different network conditions:

1. Optimum real-time phase voltage regulation in LV networks;
2. Capacity sharing between secondary substations with complementary load profiles where spare capacity is available;
3. Provision of an LVDC supply for Electric Vehicle charging and LED street lighting.
4. Cancelling the imbalance load seen from downstream LV network.

The LV Engine solution enables the LV network to be scalable, flexible and adaptable to accommodate the uptake of LCT demand and generation. LV Engine trialled SSTs in different schemes, monitored their performance compared with conventional reinforcement and transformers fitted with on-load tap changers (OLTC).

This comparison will inform a series of technical and financial guidance documents for the selection of future LV network reinforcement solutions which deliver the best value for money for UK electricity customers.

Work carried out

LV Engine was managed under seven distinctive work packages and delivered the majority of the Project's initial aims and objectives. Since 2018, extensive work was carried out, together with project partners, to develop a solution that can be successfully and safely trialled in a public distribution network. The key work carried out, under each work package, is described in the following:

Work Package 1 – Technical Design:

This work package includes all the activities relevant to developing technical specifications and system studies to conform the functional and technical specifications of the LV Engine devices. We also carried out significant work on trial site selections, to ensure LV Engine schemes can demonstrate their functions with adequate learnings generated.

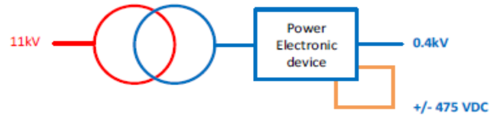
Work Package 2 – Partner selection and procurement

SP Energy Networks conducted rigorous LV Engine partner selection through a competitive tendering arrangement which resulted in three key project partners being selected. Each tendering process required resource intense activities such as market research, technical interviews, due diligence, legal reviews and commercial discussions. Nonetheless, we have learnt that there is a better value for money if the key project partners are selected through competitive tendering as part of project delivery and after developing detailed technical specifications.

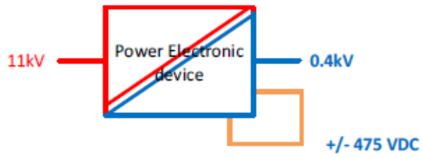
Work Package 3 – Design & Manufacturing of SSTs

Following a competitive tender, conducted in 2019, ERMCO was appointed as LV Engine SST manufacturing partner in November 2019. After staff mobilisation, ERMCO commenced the design process for both SST Topologies in early Q1 2020. The design process was initiated through the Project Inception phase, where regular detailed discussions with the SPEN team were held to translate each of the technical/functional requirements specified within the Smart Transformer Technical Specifications1 (LV Engine's Deliverable #1) to an element of the electrical, control and mechanical design.

As the focus of the LV Engine project is to demonstrate the performance of the Core Functionalities required by the network, different SST innovative topologies may provide these Core Functionalities in an efficient and reliable manner at secondary substation. There are different possible SST topologies which have been considered as products of LV Engine:



Topology 1 - Topology using a conventional distribution transformer –This topology uses power electronics devices at the secondary side of conventional transformers (11AkV/LV). The power electronic devices can be added to the existing distribution transformers to deliver the Core Functionalities of LV Engine.



Topology 2 - Topology using a High Frequency (HF) transformer – Using HF Transformers and power electronics may allow a modular and compact design while delivering the LV Engine Core Functionalities. We recognised that this topology may require a larger effort for design and manufacturing compared to Topology 1 solution.

LV Engine progressed both topologies in parallel. However, after completion of the critical design stage and benchtop testing, it became more apparent that a Topology 2 product is most likely to remain a low-level technology readiness prototype with little confidence in trialling it in the network within the LV Engine project lifetime. To avoid expending unnecessary effort developing a product that will remain at a factory prototype level and also ensure value for money for the activities in LV Engine, only Topology 1 was progressed into design, manufacturing and trial. This decision did not affect the business case initially constructed on the core functionalities targeted by LV Engine.

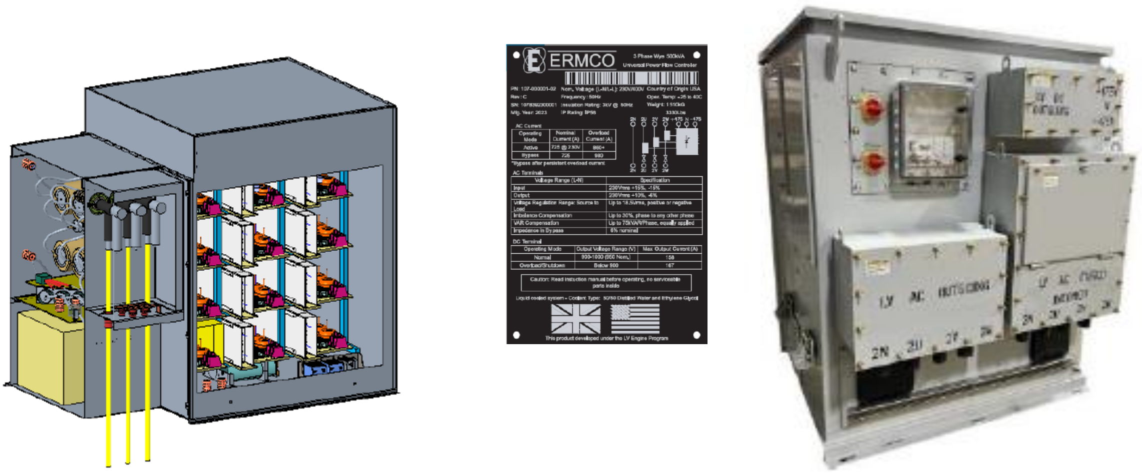


Figure 1 LV Engine SST Topogy 2 (mechanical design) (left) and LV Engine SST Topology 1 (right)

Work Package 4 – Network Integration Testing

One of the key challenges, in this project was to ensure the equipment developed separately, by different manufacturing partners collaborating to deliver against the LV Engine objectives. As planned in the original project programme, we arranged an independent test at Power Network Demonstration Centre (PNDC) to confirm the LV Engine solution works as expected, so any network live trial of LV Engine would be de-risked.

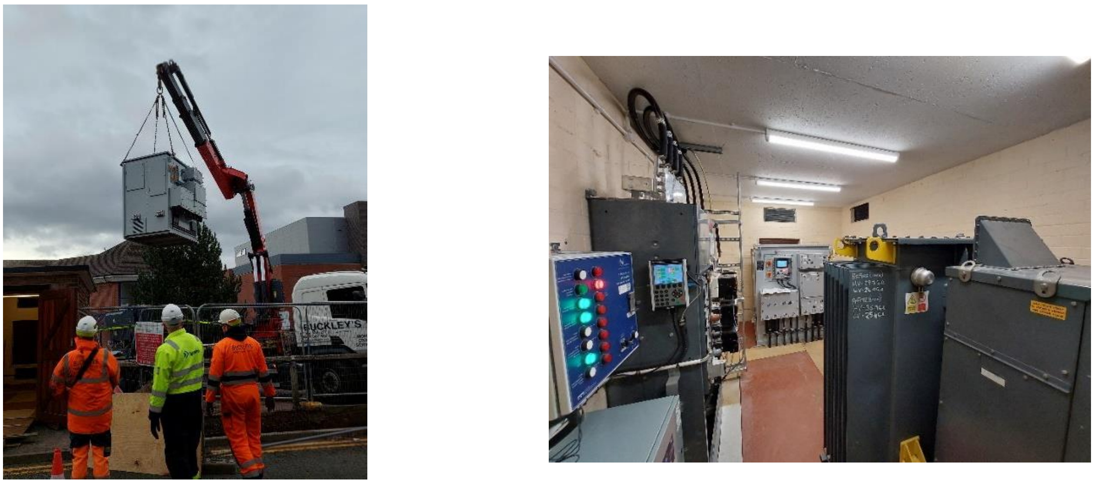
This test allowed us to confirm the overall performance of the LV Engine solution, which relies on different equipment manufactured, for the first time, by different vendors. The overall performance of the LV Engine solution was demonstrated in a controlled laboratory environment, replicating real network conditions. The lab-based testing was completed in two phases, with initial integration testing completed on first manufactured LV Engine equipment and subsequent regression testing was completed on version 2 of equipment. In each phase of testing, the AC and DC output of the LV Engine solution was investigated over a range of different test cases. A summary of the final test status of the LV Engine solution following the conclusion of lab testing is outlined in Table below.

Name of test	Test Status	Name of test	Status
System start up	PASS	Resistive pole to earth fault	PASS
System shut down	PASS	Operation outside statutory limits	PASS
LVDC Switchboard MCCB position	PASS	Reactive power compensation	PASS
Inter-Trip Test	PASS	Leakage relay tuning	PASS
Functional Test	PASS	Enspec (extra LV DC fault detection solution) tuning	PASS
Solid Pole to Pole Fault	PASS	Voltage regulation	PASS
Solid Pole to Earth Fault	PASS	Power Sharing	PASS
Solid pole to neutral fault	PASS	AC fault testing	PASS

Work Package 5 – Live Network Trial

After passing all the integration testing all key LV Engine equipment were delivered to SP Energy Networks trial sites for installation on the dates shown Table below. Prior to site work, a commissioning and installation method statement was developed and shared with the installation team. Online and in-person training sessions were also carried out to ensure all the risks are captured and mitigation plans are in place. This is particularly essential for work on new equipment and installation in a small space close to public pathways.

Item	Delivery Date	Target Trial site
UPFC S2	23 Oct 2023	Falkirk
UPFC S3	23 June 2024	Wrexham
UPFC S4	29 Jan 2024	Wrexham
LV DC Switchboard	23 Oct 2023	Falkirk



Installations at Wrexham trial site

Work Package 6 – Development of Novel Approach for Transformer Selection

After a period of monitoring the performance of the LV Engine solution in the live trial was successful, the results built confidence that LV Engine can compete with conventional reinforcement solutions, such as new substations, or other emerging technologies, such as voltage regulating distribution transformers (VRDT). We developed a report (LV Engine Deliverable #7) describing LV Engine use cases, applications and a selection toolkit that can guide design engineers for techno-economic justification of this solution.

Work Package 7 – Dissemination and Knowledge Sharing

A wide range of dissemination activities were carried out, to raise awareness and share learnings with internal and external stakeholders. The dissemination included DNO workshops, a Cigre webinar, UK and international conferences and Energy Innovation Summit presentations. LV Engine was also recognised by winning prestigious IET Excellence and Innovation Gold award in 2023.

Key Issues encountered

Project encountered several technical and management issues which was resolved by the project team:

SST Testing – The first prototype failed some of the initial tests that included, i) the thermal tests at device rating and service conditions, ii) excessive overvoltage during bypass, iii) an unexpected catastrophic failure due to excessive voltage ripple on internal DC-link. To resolve these issues, the manufacturing team redesigned and procured some of the components before rerunning the tests. This contributed to the delay in the manufacturing process.

Covid-19 Pandemic – The Covid-19 Pandemic (and post pandemic period) impacted on the LV Engine hardware supply chain significantly. Most suppliers experienced a significant drop in manufacturing during the pandemic and then a resulting backlog in post pandemic manufacture because of supply chain and resource availability issues. This particularly affected three components in LV Engine: SST, DC ultra rapid EV charger and LVDC switchboard. The resource availabilities were also significantly affected within SPEN and all project partner teams.

SST Topology 2 manufacturing – After manufacturing HV modules of SST Topology 1 and passing initial factory tests, we concluded that building the SST Topology 2 cannot offer a technically and economically justifiable solution. The continuation of this product could have caused the project further delay and overspend. Therefore, we decided to halt that development and instead focus on SST Topology 1 to ensure a commercially ready product will be available by project completion.

Key Lessons Learnt

The Project demonstrated that LV Engine solution can be effective to resolve growing thermal and voltage issues in LV Networks especially by deploying voltage control, power sharing and imbalance load cancellation functions.

Approved LV DC metering, for energy billing purposes, is the main showstopper for LVDC solution roll outs. We recommended that the LV DC element to be taken out of BaU Smart Transformers and only focus on AC functionalities in the next generation of LV Engine solutions. This compromise will reduce the unit cost and increase the chance of LV Engine solution roll out.

Early market engagement is very important, when development of a new technologies is intended. This allowed identifying the manufacturing challenges and project risks and clarify SPEN expectation from the project at early stage before procurement. We engaged with at least 8 manufacturers prior to procurement. That engagement allowed the Project to make informed decisions when pursuing two SST topologies, in parallel, for de-risking LV Engine project delivery.

Planned Implementation

Considering the learning gathered from LV Engine implementation and results of trial site, we built confidence that LV Engine solution can be effective for the growing issues that DNOs are facing in LV Networks. On that basis, we intend to follow an ambitious plan to work towards a roadmap to bring this solution to the business and have wider deployment of this unit. The roadmap includes brining the manufacturing capabilities in the UK, manufacture the second generation of the unit and install further units within RIIO-ED2 and ED3 regulatory periods.

1 Project background

1.1 Problem Statement

The electricity network in the UK is experiencing significant changes in the way energy is generated and consumed due to the growing integration of LCTs. The UK government's intention to electrify the transportation and heating sectors will result in an increase in network demand despite improvements in energy efficiency. The growing connection of distributed generation (DG) is also causing an additional strain on the LV network. The conventional "fit-and-forget" approach to the design of our LV networks is no longer a cost-effective solution to accommodate an increasing uptake in LCTs. Conventional network reinforcement does not represent value for money for our electricity customers for the following reasons:

Uncertainties in LCTs growth: The level and time horizon of the changes in demand and generation due to LCTs integration are difficult to predict as they depend on customer behaviour, technology maturity, costs of LCTs and also government policies. Conventionally, LV networks are passive and designed for the worst demand and generation conditions. Considering a wide range of scenarios for LCTs growth, the conventional planning approach can result in prohibitively expensive and unnecessary LV network investment. Consequently, the LV network requires additional flexibility and adaptability to cope with this uncertainty in LCT growth.

Increase in demand and LV DG connections: Although there are uncertainties in the levels of demand and DG growth, all future scenarios show an increase in LCT uptake. EVs are expected to grow significantly both in the total number of vehicles and the average size of EV charging points (increasing from 3.3kW in 2016 to 7.0kW by 2040). NG FES predicts that there will be 9.7 million EVs on the road by 2040. In addition, heat pumps are becoming the desirable option as the primary heat source for households and are projected to reach around 9.1m installation across GB by 2040.

The additional demand caused by EVs' and heat pumps' is very likely to coincide with the traditional winter peak demand doubling or even tripling the peak demand from each household. This could cause both significant voltage drops in the LV network and thermal stress on network assets. In addition, connection of G83 DG, mainly in the form of Photovoltaics (PVs), has been growing in LV networks and it is very likely that we will see more clustered connection of PVs in the future. This growing connection of PVs will cause overvoltage and reverse power flow issues in LV networks at off-peak times.

The combination of additional LCT demand and generation may drastically increase the daily voltage variation on the LV network and result in a requirement for costly network reinforcement.

The conventional fit-and-forget operation philosophy is no longer a cost effective approach to maintain network voltage within the statuary limits. Figure 2 illustrates the daily voltage variation in LV networks when the uptake of LCT demand and generation increases.

It should be noted that within SPD & SPM licensee areas the LV network is already experiencing a strain due to unexpected load growth and the increasing penetration of LCTs, particularly photovoltaics (PV). Previous network innovation projects such as New Thames Valley Vision, LV Network Voltage Solutions have also demonstrated that LV networks in many areas will be unable to meet the demands of increased LCT adoption due to thermal and voltage issues.

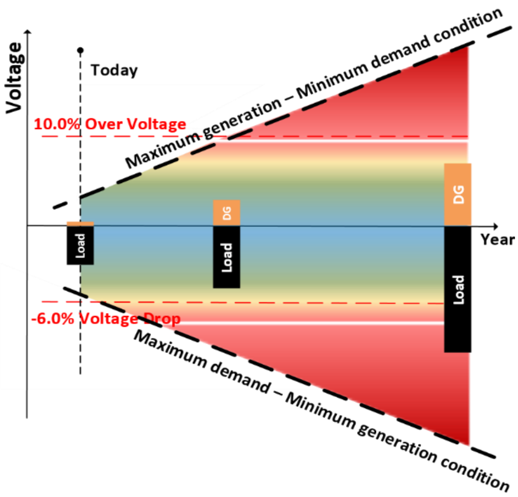


Figure 2 Illustration of LV network daily voltage variation range due to growth of LCT loads and generations. (+10% and -6% voltage statuary limits)

Increasing demand for the supply of DC power: Almost a third of household electricity demand is now from DC appliances[1]. This percentage will increase as LCTs such as EVs, HPs, and PVs become more popular in the future. DC demand is also increasing for the large commercial and industrial customers. A variety of research and innovation projects worldwide have already demonstrated the considerable benefits associated with a DC supply to electricity customers. A DC supply will allow DC generation and DC consumption to be offset against each other resulting in a reduction in the losses caused by device by device AC to DC conversion. Appendix K in Final Submission provides an overview of benefits of DC networks and the need case for DC supply. LV Engine intends to understand the value to DNOs and electricity consumers in providing a LVDC supply for EV charging and street lighting in commercial settings.

To overcome the aforementioned challenges, the traditional approach to LV network design and operation may no longer represent the best techno-economical option and an alternative approach must be found to deliver the LV network of the future. Secondary substations, as the bridge between LV and the rest of grid, can be intelligent hubs providing smart functionalities and the flexibility required for the operation of our future LV networks. Consequently, there is a

[1] Demand DC: Adoption Paths for DC Power Distribution in Homes, ACEEE, 2016

need to develop a more informed secondary substation selection process to assess the levels of smart functions required by the specific LV network based upon its characteristics, thus ensuring the network is prepared for future uses and provides value for money for UK electricity customers.

1.2 LV Engine solution

LV Engine aims to add flexibility and release additional network capacity within LV networks by informing the design and selection of a cost effective intelligent secondary transformer solution. LV Engine has the following objectives:

- Design and trial of the first UK grid connected SST for application within secondary substations;
- Provide functional specifications and control strategies for deploying the smart functionalities which an SST can provide in different network conditions;
- Compare the performance and functionalities of SSTs with those of conventional reinforcement and transformers fitted with OLTCs;
- Provide technical guidance, policy documents, a cost benefit analysis methodology and tools for the intelligent selection of future secondary transformers to ensure the Business as Usual (BaU) adoption of SST technology;
- Provide functional specifications of a fit-for-purpose network design to inform the provision of LVDC supplies to UK electricity customers from SSTs;
- Demonstrate the protection of LV networks where power electronics are used;
- Stimulate the SST market for future competitive production of this technology;
- Provide performance data together with the control algorithms to universities for further academic research and development;
- Up-skill internal staff on power electronics technologies and applications within distribution networks and the value it can bring;
- Knowledge dissemination to UK DNOs and the UK power electronics industry to facilitate the replication of the LV Engine solution across GB;
- Collaborate with our project partner, UK Power Networks, to develop a solution which can be adopted by all UK DNOs for BaU planning and operation of LV networks.

This enhances the adaptability of LV networks to enable the future uptake of LCTs. LV Engine will design and trial the first UK SST for deployment within secondary substations (11kV/0.4kV) and produce smart tools for the efficient reinforcement of future LV networks.

SSTs will be trialled within five different schemes and their performance will be technically and financially compared with conventional reinforcement and transformers fitted with on-load tap changers (OLTC).

This comparison will inform a series of technical and financial guidance documents for the selection of future LV network reinforcement solutions which deliver the best value for money for UK electricity customers.

SSTs provide multiple functionalities which can bring value to the LV network. However, LV Engine will focus and demonstrate the following preliminary smart SST functionalities under different network conditions:

1- Optimum real-time phase voltage regulation in LV networks;
2- Capacity sharing between secondary substations with complementary load profiles where spare capacity is available;
3- Fault level control to allow meshed LV network operation;
4- Provision of an LVDC supply for Electric Vehicle charging and LED street lighting.

The LV Engine solution enables the LV network to be scalable, flexible and adaptable to accommodate the uptake of LCT demand and generation.

2 Details of the Work Carried Out

LV Engine was managed under seven distinctive work packages and delivered the majority of its initial aims and objectives. Extensive work was carried out together with project partners since 2017 to develop a solution that can be successfully and safely trialled in public distribution networks. The key work carried out under each work package is described in the following sections.

2.1 Work package 1 – Technical Design

This work package includes all the activities relevant to developing technical specifications and system studies to conform the functional and technical specifications of the LV Engine devices. We also carried out significant work on trial site selections to ensure LV Engine schemes can demonstrate their functions with adequate learnings generated. The following key works carried out under this work package:

2.1.1 Developing technical specifications

Technical and functional specifications were developed for devices that were deployed specifically for LV Engine demonstration. These specifications were developed with extensive engagement with our internal experts, external consultants and manufacturer engagement. We developed technical specifications for 4 devices:

- Power Electronic technology – SST Topology 1 and SST Topology 2.
- LV DC Switchboard – The LVDC switchboard including the DC circuit breakers that was used in the LVDC supply scheme.
- *LV Controlled Circuit Breaker* – LV circuit breaker that can be remotely open/close to form interconnection between neighbouring substations.
- LV Engine control display and communication cabinet – A device that is used to display the status of LVDC circuit breakers, and other normally Open/Close contacts and house the router for communication.

For developing the technical specification of each solution, in particular the power electronic technologies, we carried out a collaborative development with a range of project partners and potential manufacturing partners under the following steps:

- Fresh market research was conducted to understand the status of technology and the key players in the market
- The relevant standards and other technical specifications were identified, this was conducted in collaboration with academic partners our internal team
- System-level technical specifications was developed, where all the grid interfaces and safety requirements were captured
- The technical specifications document was shared with shortlisted manufacturers and comments on manufacturing issues, costings and technical risks were collated
- The technical specifications Updated and finalised where required
- The key outcome of this activity was LV Engine deliverable #1 – Technical and functional specifications of SST.

2.1.2 Trial site selections

Extensive work was carried out to engage with our network design and operation teams to short list potential sites that can satisfy LV Engine scheme objectives. Identifying the LVDC trial site was also undertaken with extensive engagement with potential LVDC customers. The following work carried out:

- Developed a document explaining site selection criteria and project objectives, some of the criteria considered were as follows: Space requirements, moderate voltage issues, neighbouring substations with complementary load profiles (e.g. residential vs commercial load profiles). We shared this document with all SP Distribution and SP Manweb eleven districts team to provide us with feedback on potential sites. In parallel, we also conducted desktop analysis on potential sites and their connectivity using our Geographical Information System (GIS). The outcome of this exercise was the list of sites that can potentially deliver LV Engine schemes.

- Developed a document for LVDC site selection and objectives of LV DC scheme demonstration. This document was shared with potential DC customers. LVDC trial site selection was a challenging exercise considering conventional customers are all set for AC connection but not DC. Nonetheless, we built a collaboration arrangement with Falkirk Council (as a customer) and Tritium (supplier of DC fed charger) to join LV Engine project.

2.1.3 Academic research and studies

Our academic partners supported us to carry out several research and studies on potential topologies of the power electronic devices, the expected LV Engine performance on trial sites, protection studies in various network and fault scenarios.

2.2 Work package 2 – Partner selection and procurement

LV Engine partner selection was undertaken through a competitive tendering arrangement, though which three key project partners were selected. Each tendering process required resource intense activities, such as market research, technical interviews, due diligence, legal reviews and commercial discussions. Nonetheless, we believe, there is a better value for money if the key project partners are selected through competitive tendering as part of project delivery and after developing detailed technical specifications. Figure 3 shows the tendering process carried out for appointments in LV Engine.

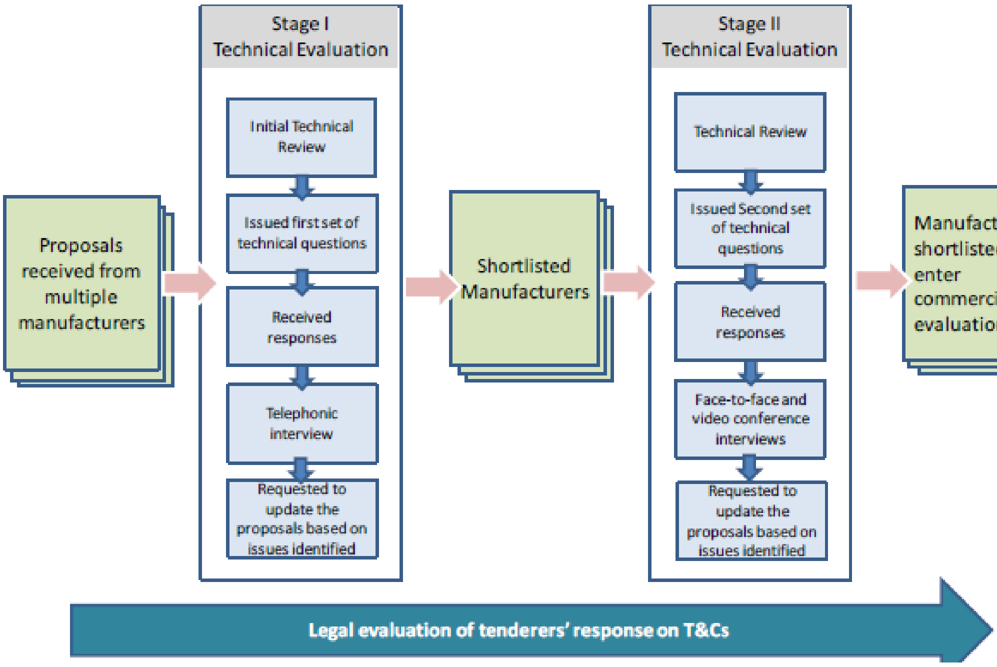


Figure 3 Procurement process conducted for partner selection.

2.3 Work package 3 – Design & Manufacturing of SSTs

Following a competitive tender conducted in 2019, ERMCO was appointed as LV Engine SST manufacturing partner in November 2019. After staff mobilisation, ERMCO commenced the design process for both SST Topologies in early Q1 2020. The design process was initiated through a project inception phase. In this phase, regular detailed discussions with the SPEN team were held to translate each of the technical/functional requirements, specified within the Smart Transformer Technical Specifications (LV Engine Deliverable #1), to an element of the electrical, control and mechanical design.

As the focus of the LV Engine project is to demonstrate the performance of the core functionalities required by the network, different SST innovative topologies may provide these core functionalities in an efficient and reliable manner at secondary substation. There are different possible SST topologies which have been considered as products of LV Engine:

> *Topology 1 - A conventional distribution transformer* –This topology uses power electronics devices at the secondary side of conventional transformers (11kV/LV). The power electronic devices can be added to the existing distribution transformers to deliver the Core Functionalities of LV Engine.

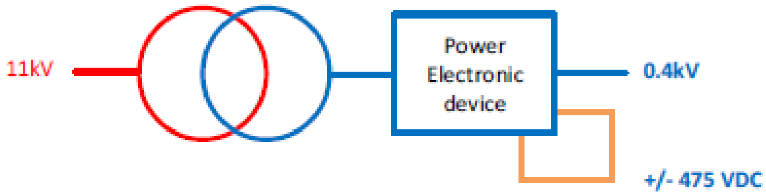


Figure 4 SST Topology 1.

Topology 2 - Topology using a High Frequency (HF) transformers – Using HF Transformers and power electronics may allow a modular and compact design while delivering the LV Engine Core Functionalities. We recognised that this topology may require a larger effort for design and manufacturing compared to Topology 1 solution.

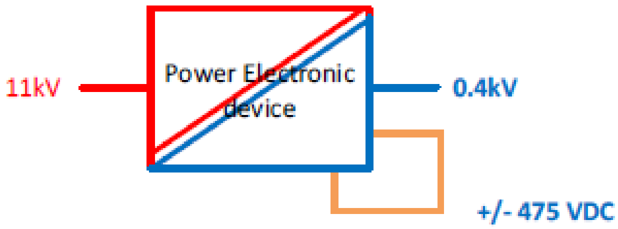


Figure 5 SST Topology 2.

2.3.1 SST Design work

The design of SST (Topology 1 and Topology 2) went through different key design stages before building the first prototype.

- Project inception – In this stage, the ERMCO and SPEN teams worked very closely to review technical specifications, identify the critical technical requirements, understand the relevant policies and standards requirements and develop initial high-level solutions.
- Initial Design – After translating technical requirements, to different aspects of the design, we worked on trade-offs in the design and optioneering for different functions. Also, extensive desktop simulations were conducted to understand the product behaviour, in different network conditions. Mechanical design and thermal management requirements were also part of this phase of design.
- Enhanced/critical design – The activities carried out in this phase of design included: Developing detailed components specifications, control and protection strategy development, terminations and network interfaces, detailed mechanical design, supply chain identifications and ordering components. Benchtop testing was also part of this stage, confirming the equipment performance identified during the supply chain identification.

LV Engine progressed both SST topologies in parallel. However, after completion of the critical design stage and benchtop testing, it became more apparent that the Topology 2 product is most likely to remain a low-level technology readiness prototype, It provided low confidence that it could be trialled on a live LV network, within LV Engine project duration. To avoid expending unnecessary effort, developing a product that will remain at a factory prototype level and also ensure value for money for the activities in LV Engine, only Topology 1 was progressed into design, manufacturing and trial. This decision did not affect the business case, initially constructed on the core functionalities targeted by LV Engine solution.

2.3.2 SST Manufacturing

To the best of our knowledge, the UPFC, designed for LV Engine, was the first of its kind, globally, , to be manufactured and tested. Like other innovation projects, there was always risks of failure during the factory testing of this product.

To i) reduce any risk to programme delay, as the results of any factory testing failure ii) build further confidence in the blueprints for unit assembly, and iii) have the opportunity for parallel testing, ERMCO proposed to build four initial engineering units which were similar, if not the same, to the final products, but these engineering units would be used only for testing at the factory and independent test centres. The summary of manufacturing steps, to reach the final product is as follows:

Step 1 – Building and testing E1, E2, E3 and E4 engineering units. These units went through various tests, including (but not limited to) dielectric test, thermal test, normal operation and functional tests, impulse test, and maximum short circuit test. During these tests, some issues were identified that resulted in upgrading the engineering units and repeating the factory test.

Step 2 – Building the first field unit (S1) – The learning from tests on the four engineering units provided adequate confidence to build the first fully operational UPFC which can be potentially deployed in the field and shipped to the UK. In line with the project programme, SP Energy Networks, in collaboration with the Power Network Demonstration Centre (PNDC) team, carried out integration testing on S1. In this test, S1 was tested in normal operating and fault conditions extensively. The results of these tests have been published in LV Engine Deliverable #4 in details. We identified a number of control and firmware issues during S1 testing and how this unit should work with the existing LV networks protection arrangement.

Step 3 – Building the second field unit (S2) – Following the learning gathered from tests on S1, ERMCO built an improved unit (S2) and shipped to the UK. SP Energy Networks and the PNDC team repeated the integration tests on S2 to confirm all issues have been addressed and the unit is ready for network deployment. After S2 successfully passed all the tests, S2 was transported to a newly built substation in Scotland. S2 was successfully commissioned in November 2023 and is still operational at the time of writing this report.

Step 4 – Building the third and fourth field units (S3 and S4) – Successful commissioning of S2 gave the team confidence to manufacture further units for deploying in other trial sites, earmarked for the project, in Wales. S3 and S4 units were successfully commissioned in two separate substations in January and June 2024, respectively. S3 and S4 are still operational with no issue at the time of writing this report.

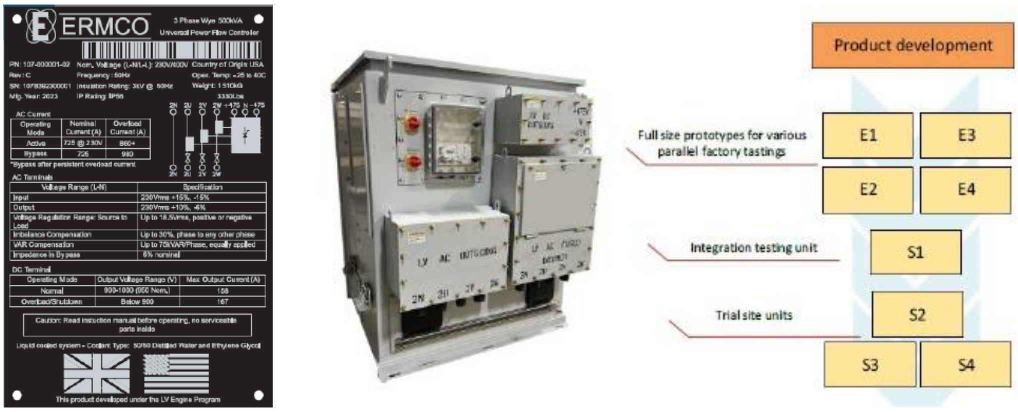


Figure 6 Nameplate, and product development process

2.3.3 Testing and development

The following tests were successfully carried out and all tests passed at ERMCO's manufacturing facilities prior to shipment to the UK and SP Energy Networks sites:

Functional tests

These are extensive tests to confirm UPFC delivers the core services including voltage control, power factor correction, imbalance load cancellation and DC supply. These services were tested at different loading conditions and different environment conditions up to 40 ºC ambient temperature.

Protection system tests

One of the key requirements for UPFC is to not compromise the existing LV network protection arrangement and also be able to protect itself in case of external or internal faults. The bypass system designed and manufactured for UPFC to protect/bypass the unit at the time of external fault was tested under short circuit scenarios. One of the key specifications that was tested was the thermal withstand capability of the bypass system in relation to upstream time link fuses at ring main unit and downstream LV way fuses (315A gg).

Short circuit withstand tests

Short circuit withstand for up to (~15kA rms) which is the same requirements for the 500kVA distribution transformer was tested at an KEMA independent laboratory, see Figure 7.

Lightning Surge Immunity Test

Lightning Surge Immunity Testing is a set of tests that are performed to qualify the power system's ability to withstand a voltage surge that models a lightning strike or switching surge. The testing is typically performed by applying a 1.2/50 usec voltage surge pulse of an operator's elected amplitude in positive and negative polarities with the expectation of no impact to the system under test.

High potential tests

Dielectric tests for up to 3kV were successfully passed and confirm the adequacy of insulation design.

Harmonic Testing

The operational resilience was tested by confirming the UPFC normal operation and at regulation when connecting to a grid with 8% voltage total harmonic distortion (THD).

Graphic User Interface (GUI) tests

A GUI developed for UPFC during LV Engine project, see Figure 8. This GUI can be installed on a user laptop and allow users to connect via ethernet to the device locally to view various alarms, parameters and download internal databases.

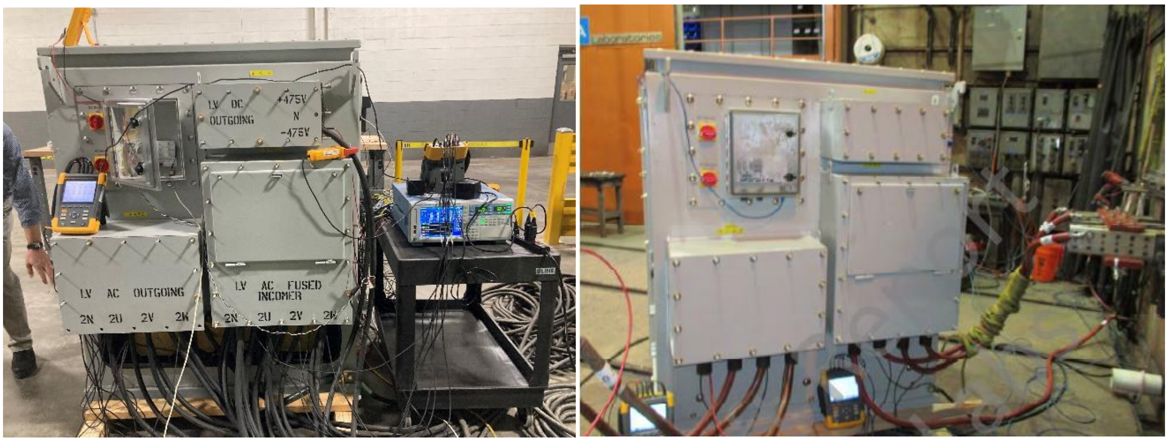


Figure 7 SST Topology 1 (UPFC) under functional (left) and short circuit tests(right)

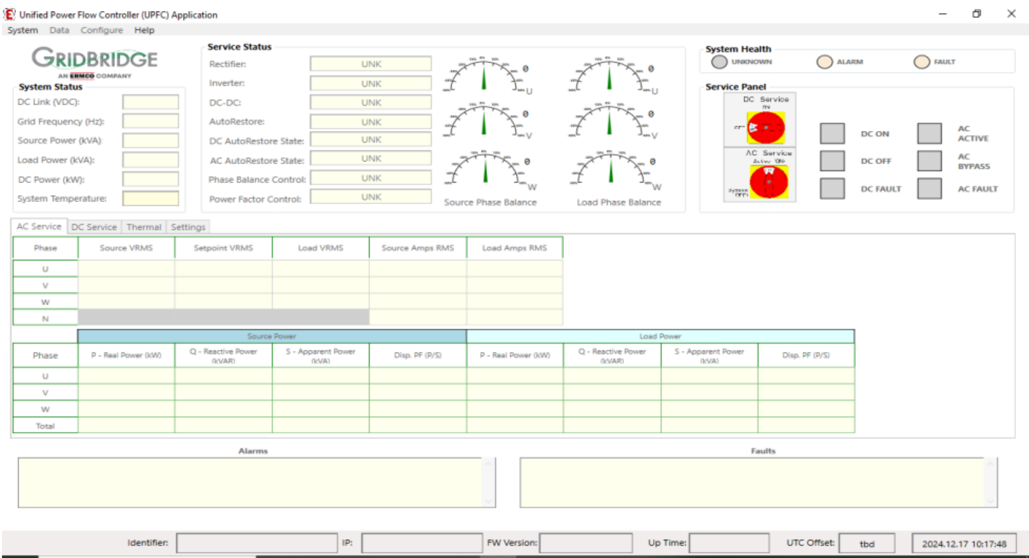


Figure 8 Graphic User Interface for interfacing with SST Topology 1 (UPFC)

2.3.4 SST Topology 2 development & halt

The design, build and benchtop testing of SST Topology 2 progressed in parallel with SST Topology 1 developments. Figure 9 SST Topology 2 design architecture shows the design architecture of this topology. The AC/DC rectifier is composed of cascaded H-bridges to enable the circuit to handle the HV phase to internal neutral 6.35kV input using commercially available 2.0 kV semiconductors.

Cascaded multilevel converter has advantages over other multilevel topologies in terms of modularisation, extendibility, and minimization of power semiconductors. It could provide bidirectional power flow with STATCOM capability, reduce harmonic distortion on the AC side and provide accurate regulation for DC link. The number of cascaded H-bridge stages is determined by the maximum voltage across each module. In our initial design we considered 8 cascaded H-bridge stages which were architected as 4 Stackable High Voltage Modules (SHVMs), where each SHVM is composed of 2 cascaded HV to LV converters. Figure 10 shows one of the SHVM which was successfully built and tested. We decided to use hard duty transparent enclosures to allow visual inspection during the test.

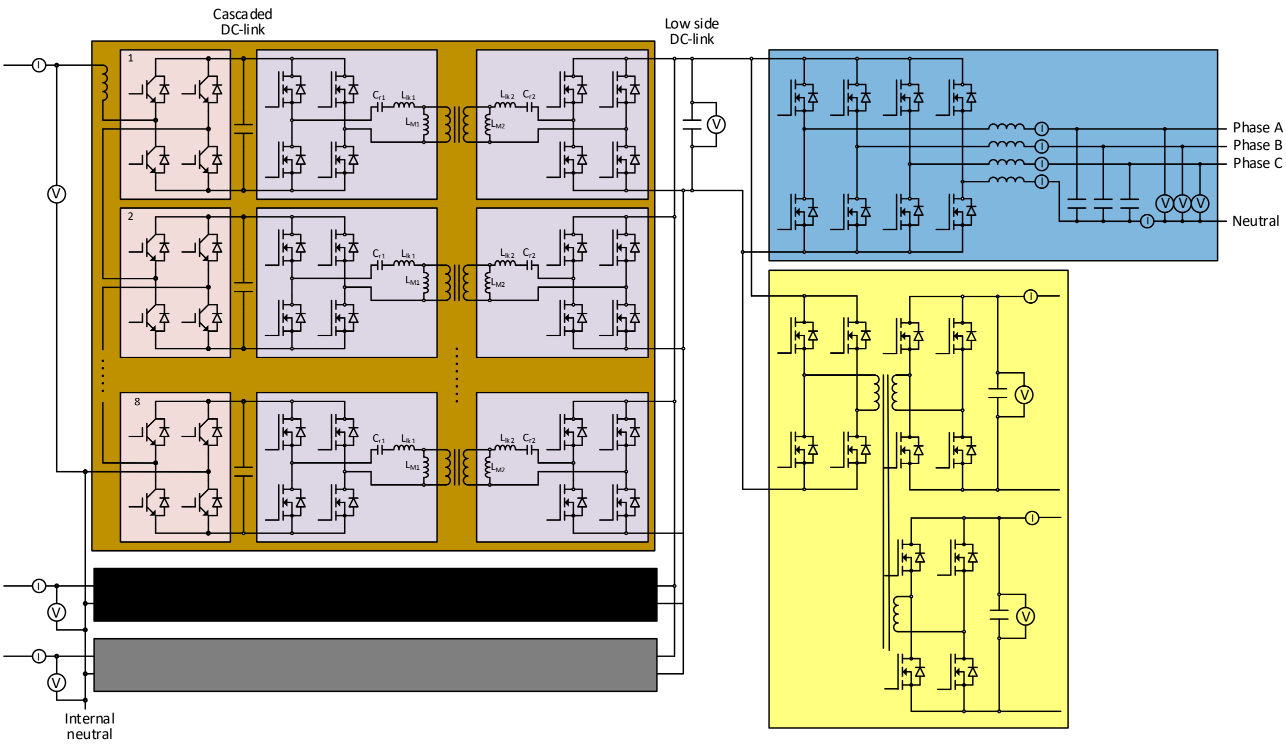
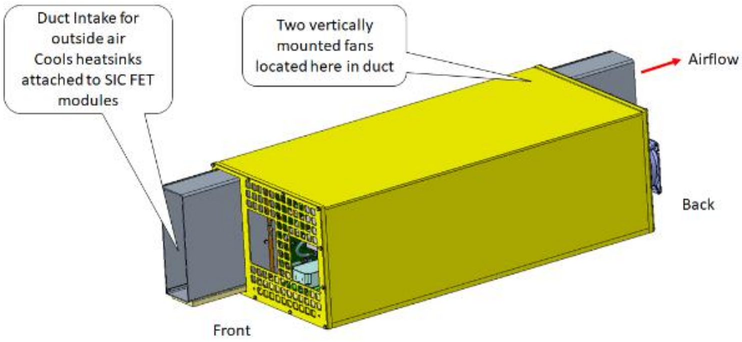


Figure 9 SST Topology 2 design architecture



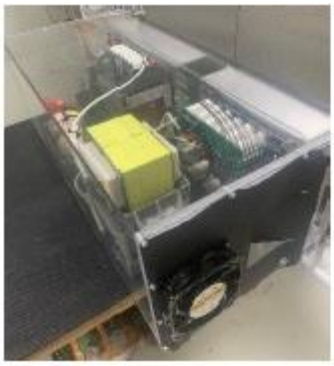


Figure 10 Stackable High Voltage Modules

HV cabinet design was also progressed to allow for adequate space for SHVMs fittings, cooling systems, terminations etc, see Figure 11. A separate cabinet for the LV AC and LVDC components and terminations were also considered. The Team decided to have a cable connection arrangement between the HV cabinet and LV cabinet. This provided better flexibility within the substation depending on the dimensions of the substation and available space.

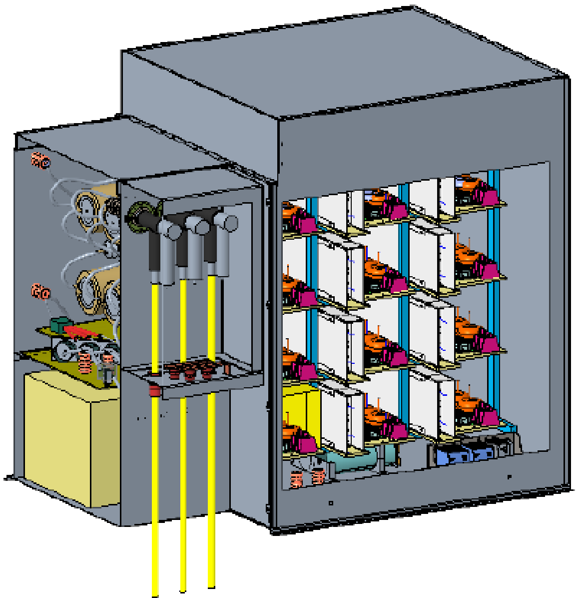


Figure 11 SST Topology 2 HV cabinet design

Although we significantly progressed on the design and benchtop testing, we concluded that SST Topology 2 will not reach to a technology readiness level (~8) that we initially intended.

We learnt that the existing semiconductor technologies (in the time of this development) would not result in a product that can be replicated for roll out. The highest voltage rating for Sic Mosfets that were commercially available was around 2.0kV, that requires at least 4 modules to stack up in each phase for 11kV network interface. We spent significant time designing and testing the HV SST layout and practicalities in terms of installations on site. The final dimensions of this product and process required for site installation did not offer a solution that we can replicate the solution after project completion. We believe that with technology advance higher voltage Sic Mosfets will be available in near future that fundamentally change the design and size of this product. Therefore, to avoid any extra effort that will result in project overspend and delay, we decided to stop development of SST Topology 2. This decision did not have any impact on the core functionality intended to be delivered by LV Engine solution.

2.3.5 Other equipment

In addition to the effort on design and manufacturing SST units, we designed and manufactured two other products in the project.

- **LV DC switchboard** - This was manufactured by Schneider Electric, Figure 12. The switchboard accepts the DC output from the UPFC. The main function of the switchboard is to distribute power to DC customers. Additionally, the switchboard houses protection and isolation equipment. The LVDC distribution board is fitted with disconnectors, Moulded Case Circuit Breakers (MCCB) and under-voltage release relays. Furthermore, an earth leakage protection relay is installed in the distribution board measuring current through the earth-neutral link. The Bender RCMB301 earth leakage protection relay has been selected to deliver this function. The suitability of this relay has been confirmed previously following tests independently carried out at Power Network Demonstration Centre.

Figure 12 – LV DC switchboard

- **Local Control System (LCS)** - This is an alarm display and telecoms panel, designed specifically for LV Engine, Figure 13. The panel provides status indications of the substation plant. A router, communicating the monitored data, is also fitted within the panel.

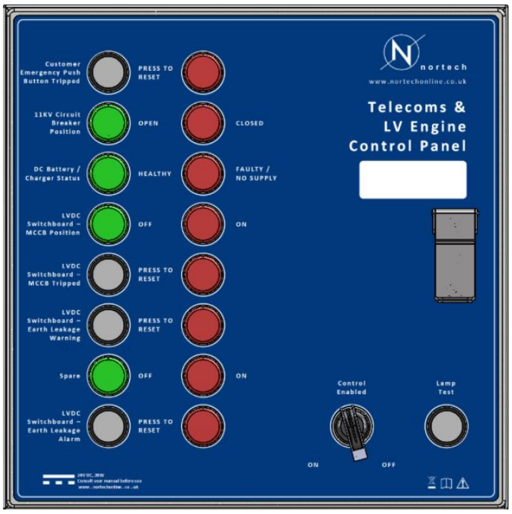


Figure 13 – Local Control system

2.4 Work package 4 – Network Integration Testing

One of the key challenges in this project was to ensure the equipment developed separately in collaboration by different manufacturing partners works together in harmony to deliver against the LV Engine objectives. As planned in original project programme, we arranged an independent test at PNDC to confirm the LV Engine solution works as expected.

This test allowed us to confirm the overall performance of the LV Engine solution which relies on different equipment manufactured for the first time by different vendors. The overall performance of the LV Engine solution was demonstrated in a controlled laboratory environment replicating real network conditions. The lab-based testing enabled the validation of all the designs and studies de-risking key LV Engine schemes prior to live trials. The overall lab set up is shown in Figure 14.

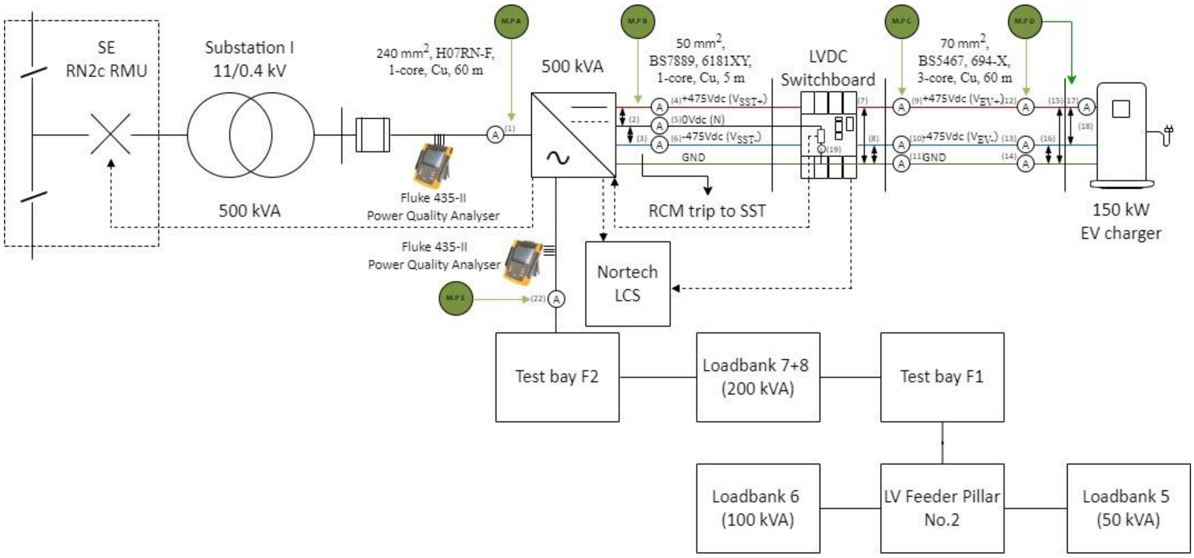


Figure 14 Network integration testing laboratory set up

Figure 15 Network integration testing laboratory set up (picture)

The lab-based testing was completed in two phases with initial integration testing completed on first LV Engine solution (S1) and subsequent regression testing was completed on version 2 (S2). In each phase of testing, the AC and DC output of the LV Engine solution was investigated over a range of different test cases. A summary of the final test status of the LV Engine solution following the conclusion of lab testing is outlined in Table 1.

Table 1 Tests carried out and results in network integration testing

Name of test	Test Status	Name of test	Test Status
System start up	PASS	Resistive pole to earth fault	PASS
System shut down	PASS	Operation outside statutory limits	PASS
LVDC Switchboard MCCB position	PASS	Reactive power compensation	PASS
Inter-Trip Test	PASS	Leakage relay tuning	PASS
Functional Test	PASS	Enspec (extra LV DC fault detection solution) tuning	PASS
Solid Pole to Pole Fault	PASS	Voltage regulation	PASS
Solid Pole to Earth Fault	PASS	Power Sharing	PASS
Solid pole to neutral fault	PASS	AC fault testing	PASS

Apart from successful operation during AC and DC faults, LV Engine equipment was extensively tested under different normal operating conditions. Figure 16 shows the operation of the LV Engine when AC load banks and DC charger are supplied at the same time. While SST Topology 1 supplied both DC and AC loads, AC voltage regulation has achieved the target voltages which were changed at various set points during the test.

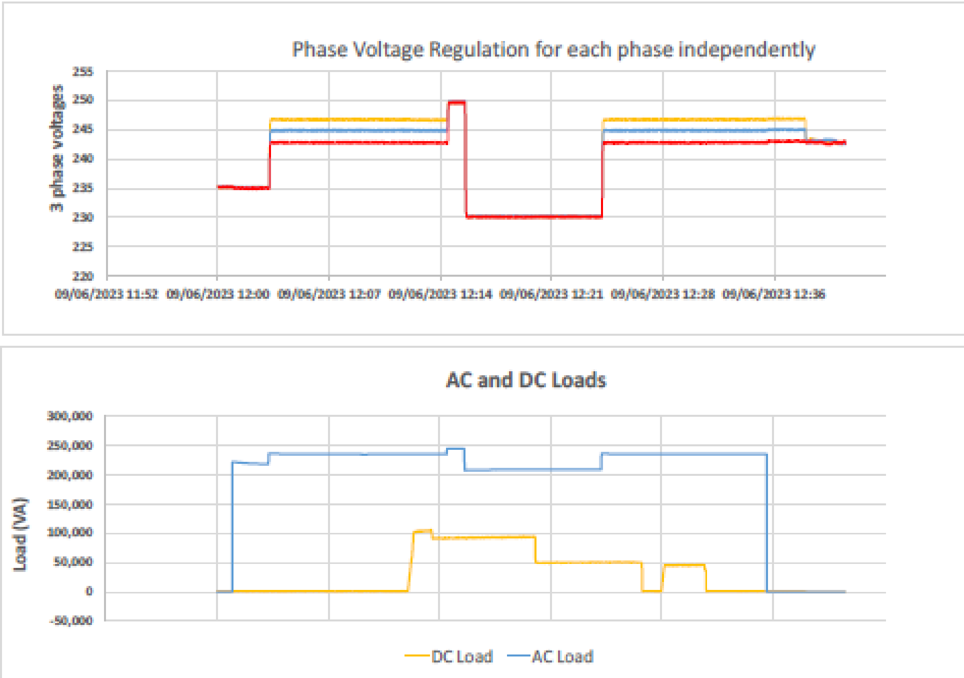


Figure 16 Results of AC/DC supply during the test at PNDC

2.5 Work package 5 – Live Network Trial

After passing all the tests, including the integration testing which is reported in LV Engine Deliverable #4, all key LV Engine equipment was delivered to SP Energy Networks trial sites for installation on the dates shown in Table 2.

Table 2 Dates that equipment delivered to LV Engine sites for installation

Item	Delivery Date	Target Trial site
UPFC S2	23 Oct 2023	Falkirk
UPFC S3	23 June 2024	Wrexham
UPFC S4	29 Jan 2024	Wrexham
LV DC Switchboard	23 Oct 2023	Falkirk

Extensive work was carried out within the LV Engine team to establish the substation layout for each trial site to ensure operational safety and no risk during installation. Each trial site was unique in terms of site dimensions and requirements for acquiring the land. We had to also consider access to different sides of UPFC to allow for inspection and maintenance. This was included in the design by considering an access door at the rear of UPFC. The three site layouts considered for our trial sites are shown in Figure 17.

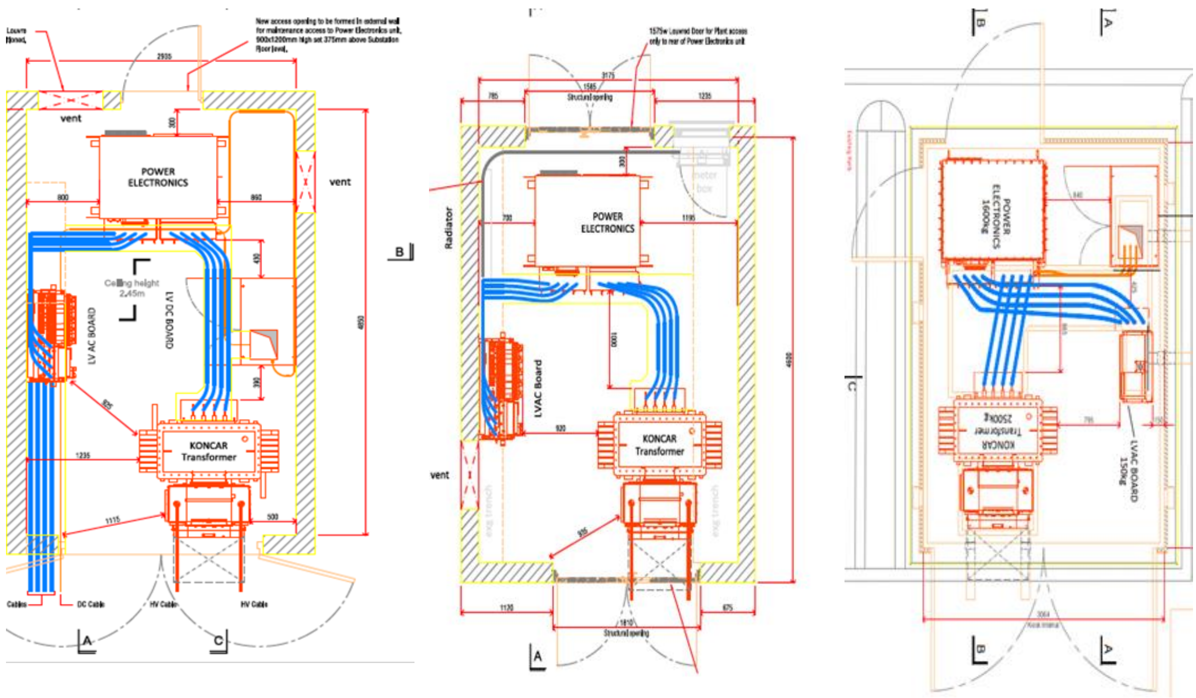


Figure 17 Substation layout for trial sites

The electrical connectivity and earthing arrangements of the substation are shown in the schematic in Figure 18. Note that due to the absence of any approved DC meter for energy billing purposes, we decided to fit the CT metering within the LV cable box of the distribution transformer which measures overall AC and DC total consumptions. Therefore our substation at Falkirk where DC is trialled, has been a dedicated substation for only one customer.

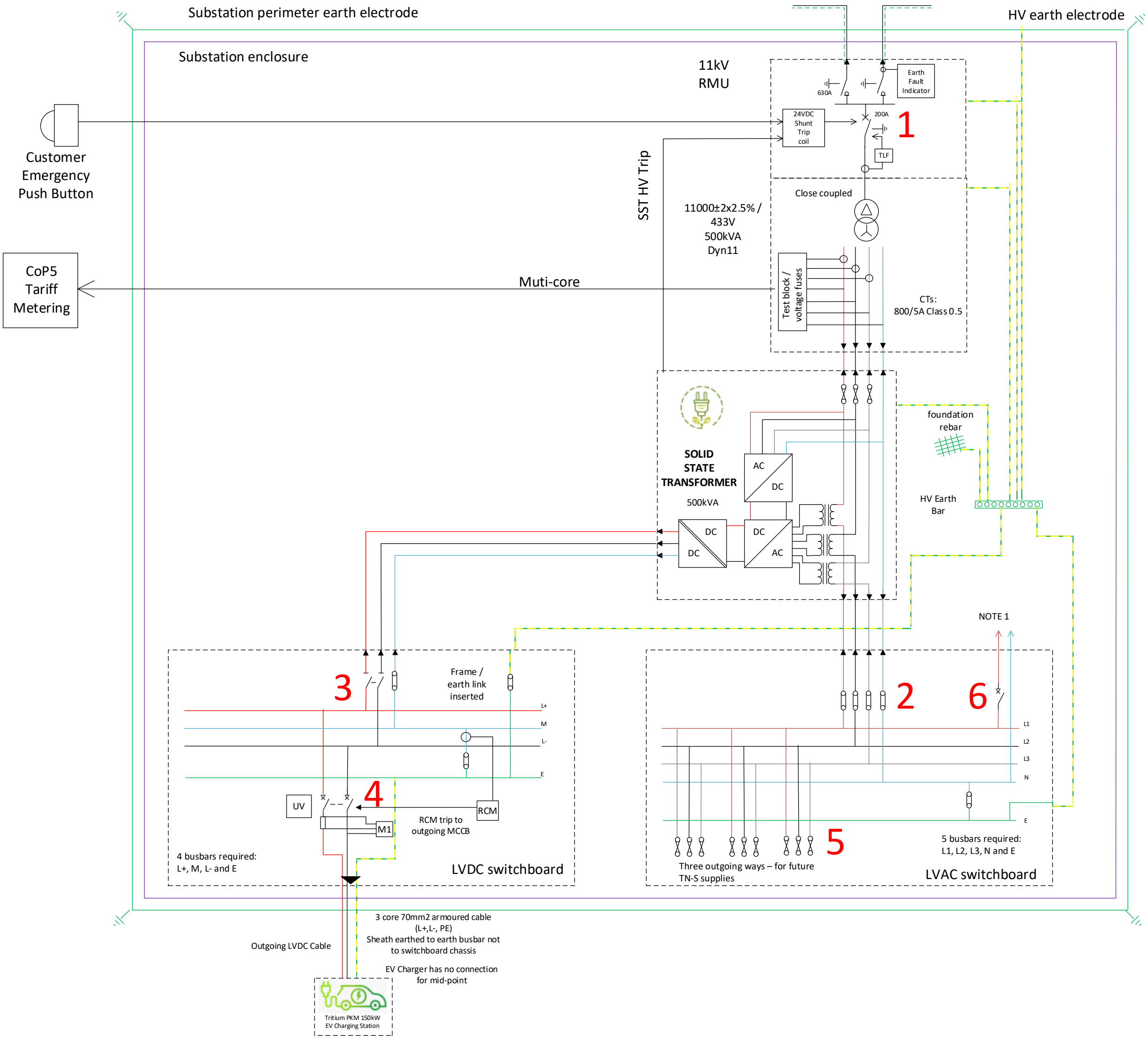


Figure 18 Trial site electrical schematic and earthing arrangement

2.6 Commissioning and installation

Prior to site work, a commissioning and installation method statement was developed and shared with the installation team. Online and in-person training sessions were also carried out to ensure all the risks are captured and mitigation plans are in place. This is particularly essential for work on new equipment and installation in a small space close to public pathways.

We also inspected all the equipment with the installation team at the depot before transferring them to the site. That exercise generated questions around fitting and securing the equipment that could then be planned for in advance of installation day.

The commissioning method statement document includes the following technical and operational guidance:

- Safety Precautions
- Substation layouts
- Civil design

- Manual handling
- Electrical connections
- Terminations and cabling requirements
- Earthing requirements
- Small wiring schematic
- System start-up and energisation procedure
- Inter tripping and alarms tests and checks
- AC services and voltage regulations tests
- DC services energisation procedure

Figure 19 and Figure 20 show the installation at Falkirk and Wrexham trial sites respectively.

Figure 19 - Installations at Wrexham trial site

Figure 20 - Installations at Falkirk trial site

2.7 Work package 6 – Development of novel approach for transformer selection

LV Engine solution can compete with conventional reinforcement solutions such as new substations or other emerging technologies such as voltage regulating distribution transformers (VRDT). We developed a report (LV Engine Deliverable #7) describing LV Engine use cases, applications and a selection toolkit that can guide design engineers for techno-economic justification of this solution. Based on the learnings from live trial performance monitoring, we provided a methodology for cost benefit analysis of LV Engine solution and what would be the criteria for selecting this solution.

We also, as part of the project, installed and monitored number of VRDT sites where we could demonstrate the performance of distribution transformers fitted with onload tap changers as a competing solution to LV Engine.

Figure 21 VRDT commissioned in Glasgow as part of LV Engine project

Table 3 Comparison on functionalities offered by LV Engine and VRDT.

Features	LV Engine	VRDT
Voltage regulation range	+/-8%	+/- 5%
Power rating	500kVA (trialled)	1MVA (approved), 500kVA (trialled)
Voltage regulation for each phase	Yes	No
Voltage regulation tuning	Fine	Coarse
Power factor correction	Yes	No

Features	LV Engine	VRDT
Operation in a meshed network	Controlled power	No control
Can be used within circuit	Yes – for voltage control and cancelling imbalanced load	No
Harmonic compensation	Yes	No
Monitoring and local analytics	Yes	Yes (but limited)
Connection method	Cable connected to existing transformer	Replacing the transformer
Cost	Almost three times a conventional transformer	Almost two times a conventional transformer

2.8 Work package 7 – Dissemination and knowledge sharing

A wide range of dissemination activities including conferences, webinars, workshops and site visits for internal and external stakeholders were carried out to raise awareness and share learnings about the project. A complete list of dissemination activities is given in section 11.

2.9 Collaboration with UK Power Networks

We experienced a successful collaboration with UK Power Networks where we could share project knowledge and learnings about two sister projects LV Engine and Active Response openly and on a regular basis. We also joined efforts to propose an ENA working group on power electronics and deliver joint dissemination events about power electronic technologies.

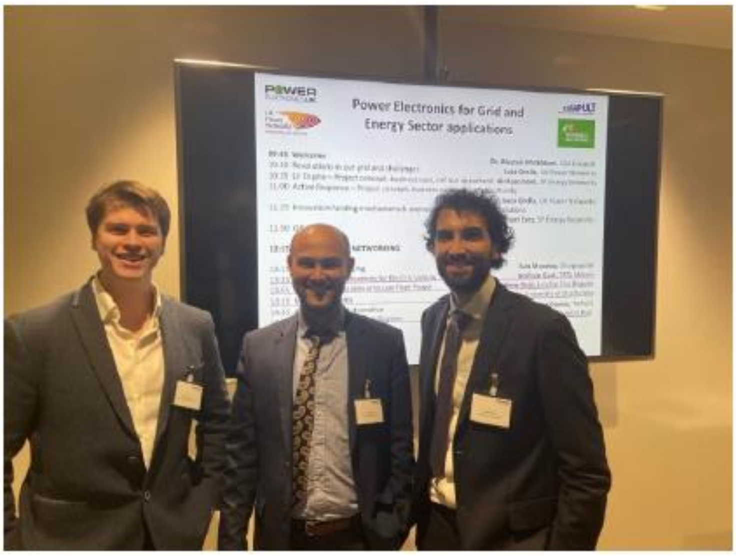


Figure 22 LV Engine & Active Response co-presented at the CSA Catapult

This included promoting the market opportunity for grid application power electronic solutions which was delivered to SMEs and UK manufacturing bodies by engaging with Compound Semiconductor Application (CSA) Catapult and Power Electronics UK.

3 The outcome of project

The LV Engine solution was successfully installed and commissioned at three sites in SP Manweb and SP Distribution license areas to deliver LV Engine planned schemes. The LV Engine substations have been operational and delivering their functionalities at the time of preparing this report. We successfully demonstrated the core functionalities targeted in the original LV Engine full proposal submissions and assessed the performance of the technology against the following field results:

- Voltage regulation;
- Capacity sharing / load balancing;
- Phase imbalance cancelation and power factor correction;
- LV customer phase identification;
- An assessment of system losses;
- An assessment of system performance whilst EV charging load is connected.

The details of all assessments have been published in LV Engine Deliverable #6 report. However, a summary of the project outcomes is presented in the following sections.

3.1 LV Engine Schemes

At the beginning of the project, five schemes were proposed for LV Engine, Figure 23:

- Scheme 1 allows an LV Engine substation to be coupled to one conventional substation to allow capacity sharing on the LV AC network between the two;
- Scheme 2 allows an LV Engine substation to be connected to two conventional substations to allow capacity sharing between the three;
- Scheme 3 allows to LV Engine substations and one conventional substation to be interconnected to allow enhanced capacity sharing;
- Scheme 4 demonstrates an LV Engine substation providing an LV DC supply;
- Scheme 5 demonstrated and LV engine substation providing an LV DC supply and LV AC supply to a network.

This report describes the trial at Crescent Road and Smith DIY where Schemes 1 to 3 were trialled and also the trial at Falkirk which was a hybrid implementation of Scheme 4 and Scheme 5. The Falkirk trials, in addition to DC supply, provides an LV AC supply connected to an LV AC distribution network, but just recently an AC fed 160kW charger was also connected to this substation completing the AC and DC supply. It should be noted that the AC and DC simultaneous supply was also demonstrated already as part of LV Engine Deliverable #4, Network Integration Testing.

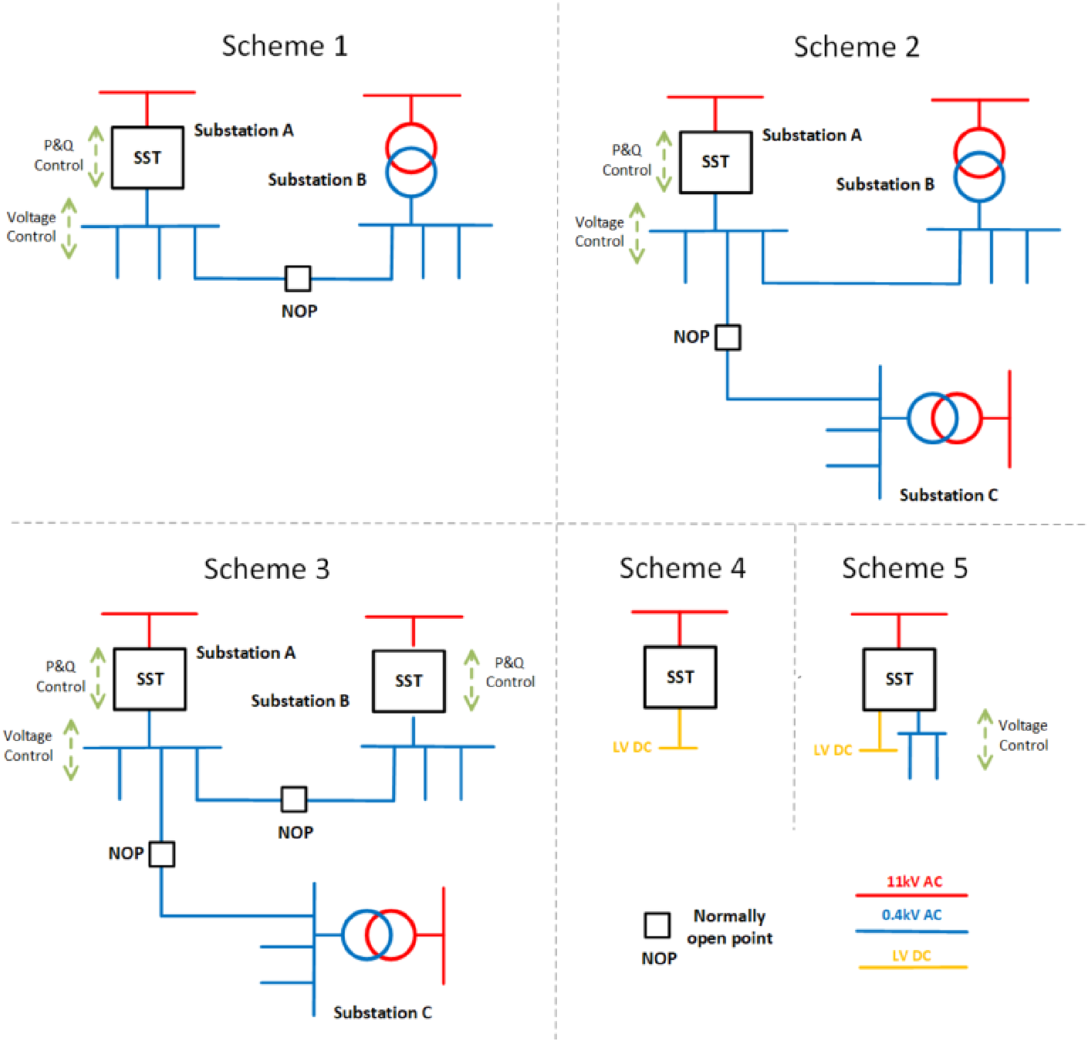


Figure 23 – Proposed schemes for LV Engine

3.1.1 Scheme 1 to 3 Trial

In this trial, two LV Engine enabled substations were trialled on the existing LV AC (0.4kV) network in the town centre, Figure 24. The LV Engine enabled substations are labelled SST (Solid State Transformer) which is a generic term used to represent a substation accommodating a UPFC (Unified Power Flow Controller).

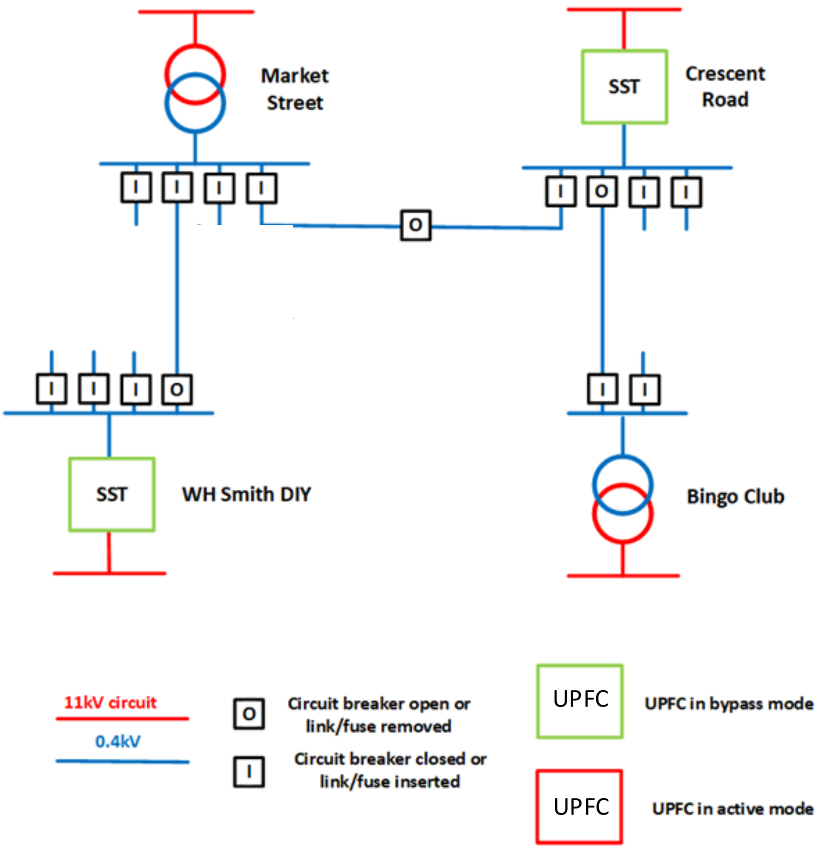


Figure 24 – Network connectivity for trialling

3.1.2 Capacity sharing between Crescent Road and Bingo Club on 11 October

The second capacity sharing test between Crescent Road and Bingo Club substations was carried out between 09:02 and 09:31 on 11 October. The circuit breaker for the interconnection between Crescent Road and Bingo Club was closed at 09:02 as shown in Figure 25, and the UPFC at Crescent Road was put into voltage control mode at 09:06 with a voltage setpoint of 243V. Subsequently, the UPFC was provided with different voltage setpoints throughout the test and the resulting changes in active and reactive power were assessed.

The active power, reactive power and the LV AC Load Voltage during the test are shown in Figure 26, and the change in active/reactive power was a result of change in voltage set. It is clear from Figure 26 that a rise in voltage at Crescent Road results in an increase in active power supplied, and a drop in voltage results in a decrease in active power.

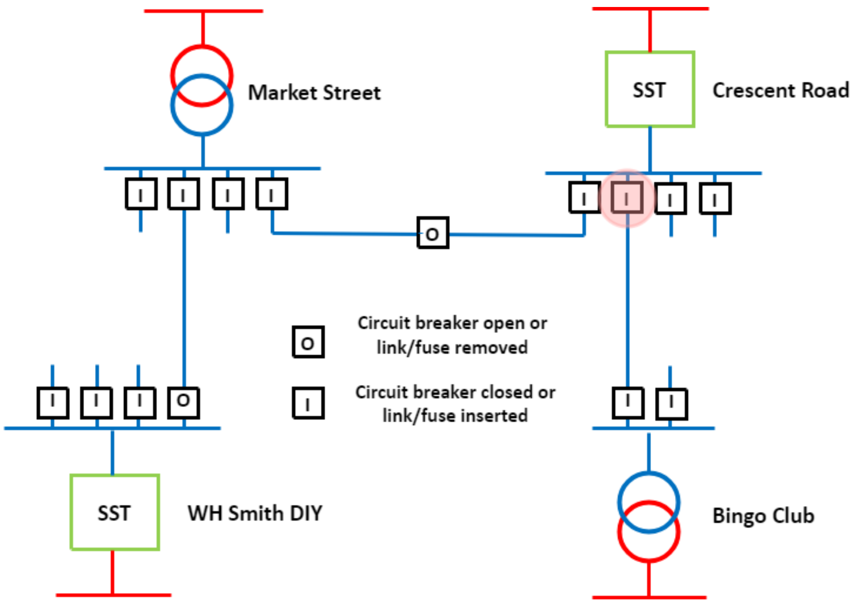


Figure 25 – Network configuration during the capacity sharing test between Crescent Road and Bingo Club

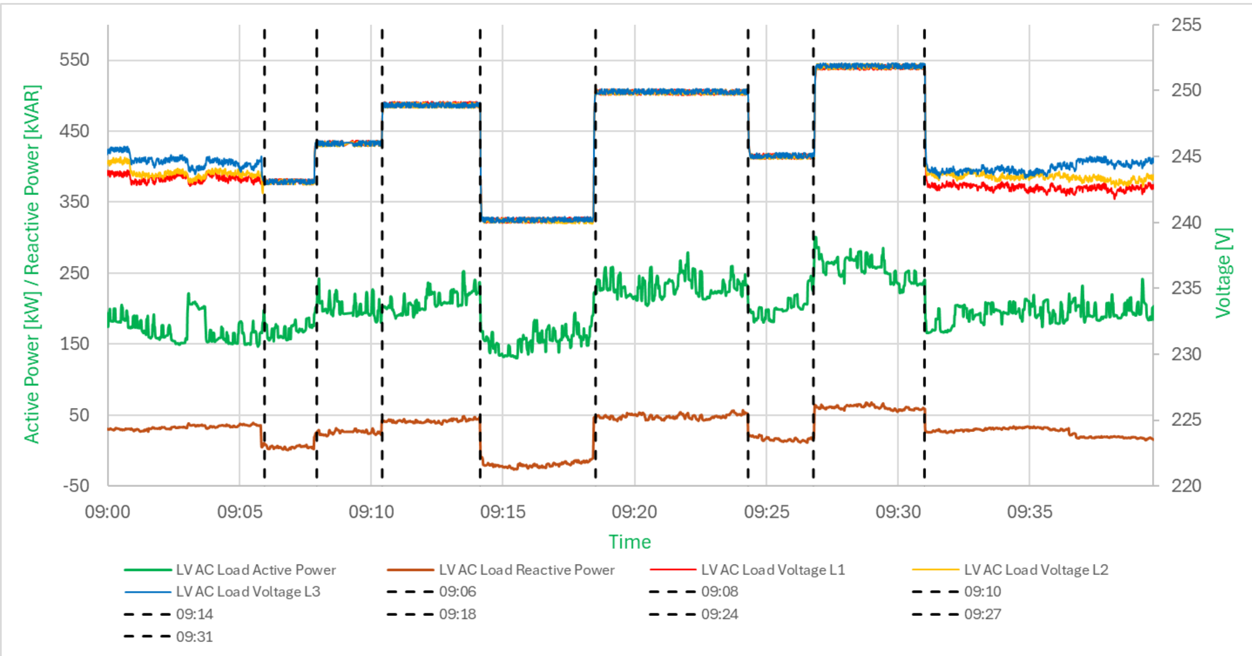


Figure 26 – Output Active power and voltage at Cresent Road during the capacity sharing test between Crescent Road and Bingo Club

3.1.3 Capacity Sharing between Crescent Road, Bingo Club, and Market Street

The capacity sharing test between Crescent Road, Bingo Club, and Market Street substations was carried out between 10:54 and 11:14 on 11 October. The circuit breakers for Crescent Road – Bingo Club interconnection, and Crescent Road – Market Street were closed at 10:54 and 10:55 respectively as shown in Figure 28. The UPFC at Crescent Road was put in voltage control mode at 11:00 and subsequently, the UPFC was provided with different voltage setpoints throughout the test and the resulting change in active power was assessed.

The active power and the LV AC Load Voltage during the test are shown in Figure 28, and the change in active power as result of change in voltage set point. It is clear from the Figure 28 and that a rise in voltage at Crescent Road results in an increase in active power supplied, and a drop results in a decrease in active power.

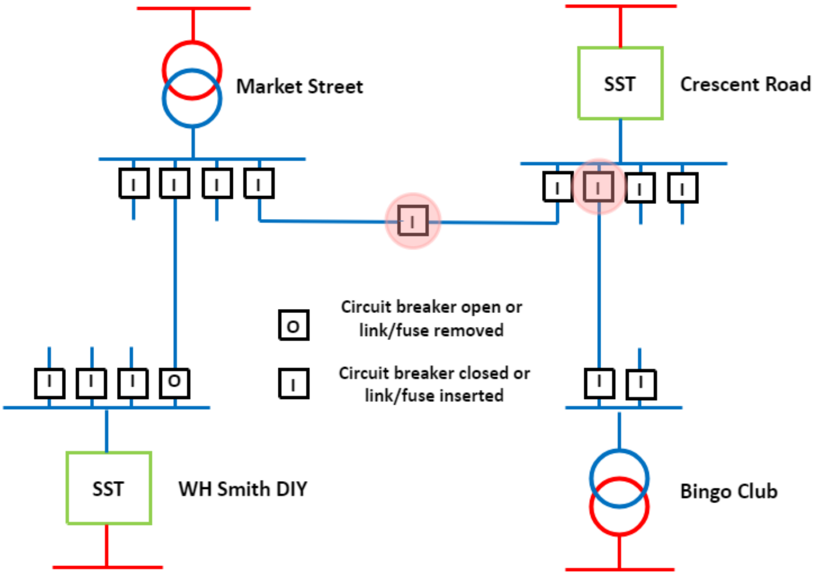


Figure 27 – Network configuration during the capacity sharing test among Crescent Road, Bingo Club and Market Street

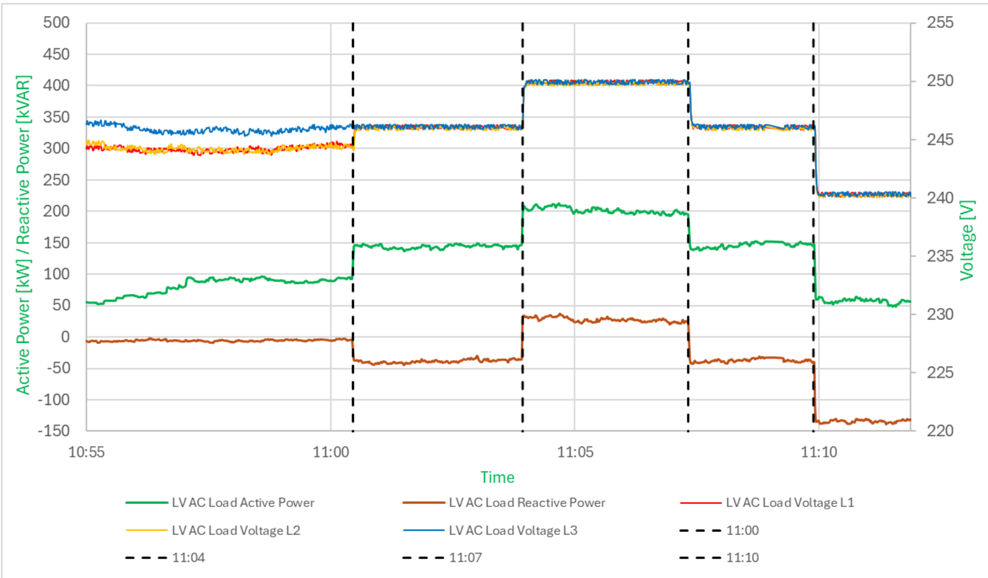


Figure 28 – Output Active power and voltage at Cresent Road during the capacity sharing test among Crescent Road, Bingo Club and Market Street

3.1.4 Capacity sharing between Crescent Road, Market Street, and Smith DIY

The capacity sharing test between Crescent Road, Market Street, and Smith DIY substations was carried out between 12:03 and 12:46 on 11 October. The circuit breakers for Crescent Road

– Market Street interconnection, and Market Street – Smith DIY interconnection were closed at 12:05 as shown in Figure 29.

Once the circuit breakers were closed, the UPFCs at both Crescent Road and Smith DIY were put in voltage control mode and provided with different voltage setpoints throughout the test and the resulting changes in active and reactive power were assessed.

The active power, reactive power and the LV AC Load Voltage at the Crescent Road substation are shown in Figure 30.

If it was only Crescent Road and Smith DIY sharing the capacity, a rise in power exported by one substation would result in an equivalent decrease in power exported by the other substation. However, this does not seem to be the case because the Market Street substation is also sharing the capacity and the measurements for power at Market Street are not available. The results shown lead to the conclusion that any change in power exported by Crescent Road or Smith DIY results in an equivalent change at Market Street substation.

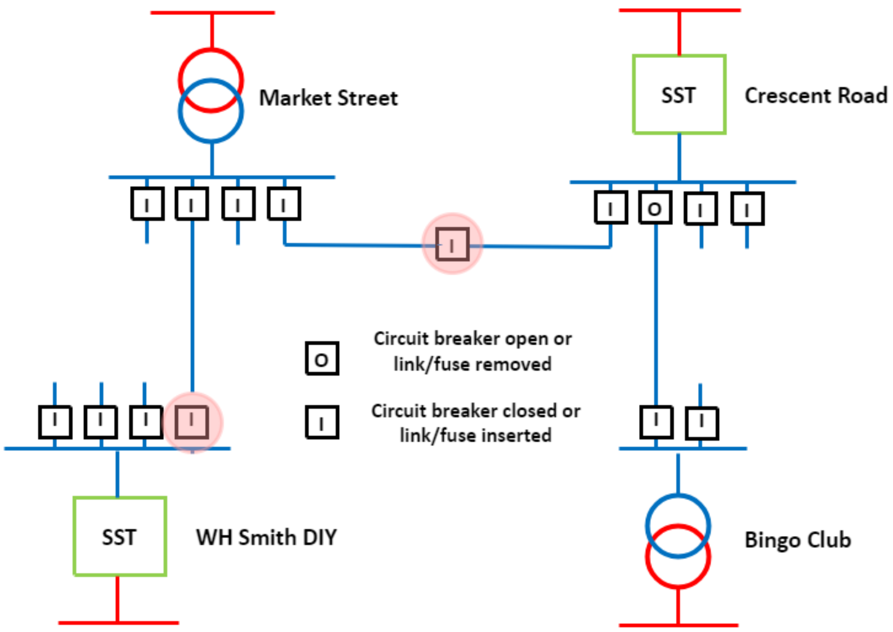


Figure 29 - Network configuration during the capacity sharing test among Crescent Road, Market Street, and Smith DIY

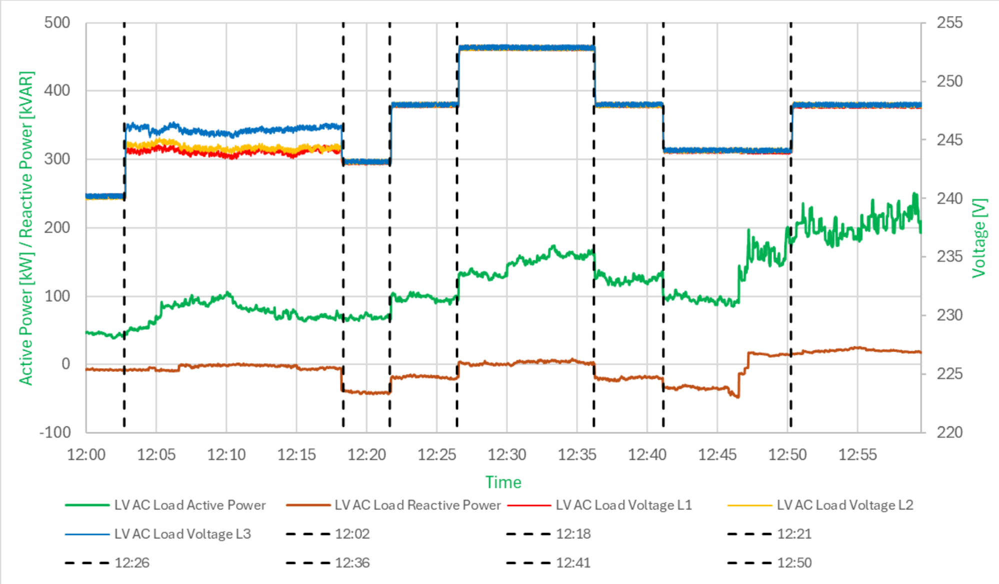


Figure 30 – Output Active power and voltage at Cresent Road during the capacity sharing test among Crescent Road, Market Street, and Smith DIY

3.1.5 Crescent Road voltage control tests

LV Engine has the capability to independently adjust voltage setpoints. This enables precise control of the output voltage across all phases. This functionality allows the UPFC to dynamically respond to varying load conditions or specific grid requirements, maintaining balance and optimising performance in real-time. By using the internal control algorithms, the UPFC adjusts each phase voltage to meet the required setpoints, ensuring stable operation even in scenarios where the phases are asymmetrical or subject to fluctuations. This design feature is critical for applications that require high reliability and flexibility in power delivery, especially when the network contains many distributed energy systems.

Results of a test carried out to test LV Engine's ability to track user-defined voltage set points are shown in Figure 31. The results show that LV Engine closely follows the voltage set points and remains stable in case of step changes to the set points.

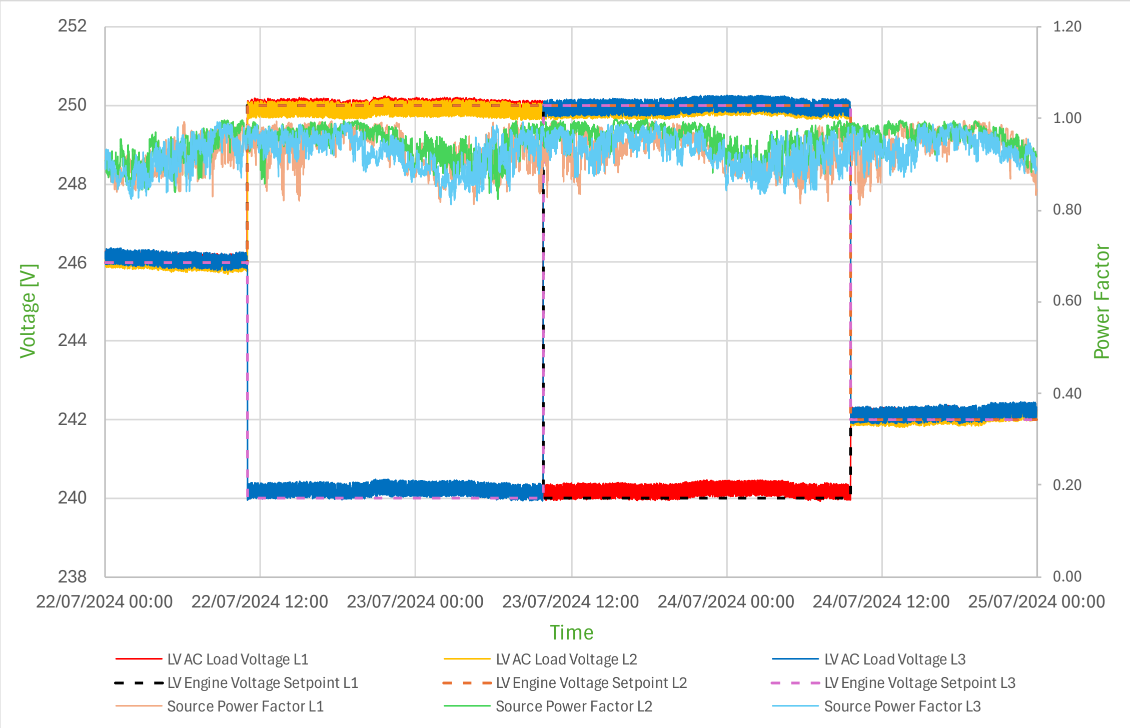


Figure 31 - Voltage set points tracking test for LV Engine system at Crescent Road

3.1.6 Crescent Road customer phase identification

Another purpose of the voltage control test described in the previous section is to perform customer phase identification, which aims to determine which customers are connected to each phase. This is achieved by varying the voltage on each phase and comparing these variations to the voltage measurements taken by the smart meters of the customers connected to those phases. By deliberately adjusting the voltage on individual phases, the resulting changes in voltage are observed on customers' smart meters. These measurements are then analysed to correlate the voltage variations with the specific phases, thereby identifying the phase to which each customer is connected. This mechanism ensures precise mapping of customers to their respective phases allowing improved visibility of the LV network and allowing future customers to be connected to phases with lower demand.

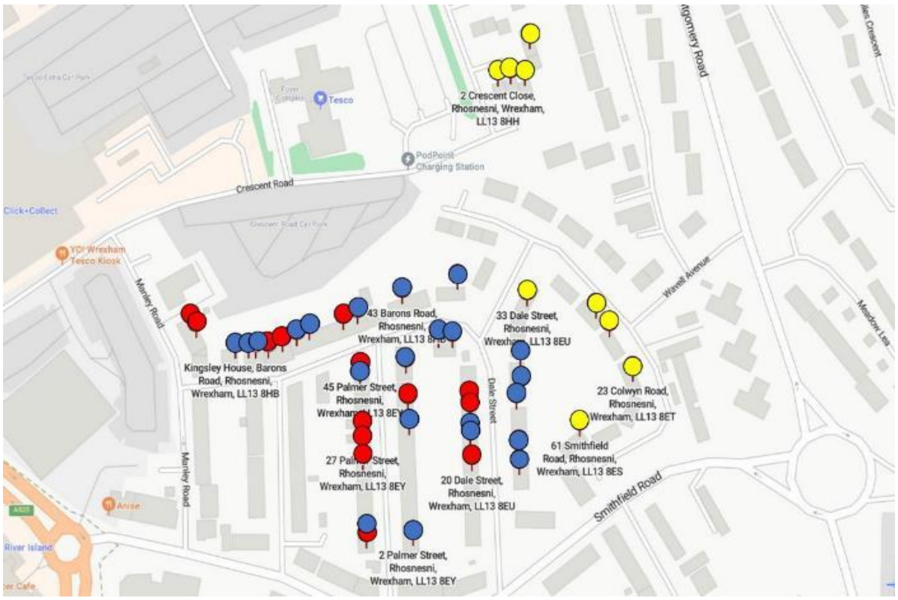


Figure 32 – Customers mapped to each of the three phases using the results of the voltage control test

3.1.7 Crescent Road phase imbalance / power factor correction test

LV Engine has the capability to manage unbalanced loads across the three phases while presenting a balanced load to the power source. When the load is unbalanced, meaning that the power demand differs across the phases, the UPFC adjusts the current drawn from the source in such a way that the source perceives a balanced load. This is achieved through advanced power electronics and control algorithms, which regulate the conversion of power between the AC and DC stages.

When this capability is enabled, the LV Engine system dynamically redistributes the power flow to ensure that the total current drawn from the source is equal across all phases. As a result, the system maintains grid stability and improves power quality, even in the presence of asymmetrical loads, reducing the risk of voltage imbalances and other issues typically associated with unbalanced loads in three-phase systems. This functionality is particularly valuable in distributed energy systems or industrial environments where load imbalances are common.

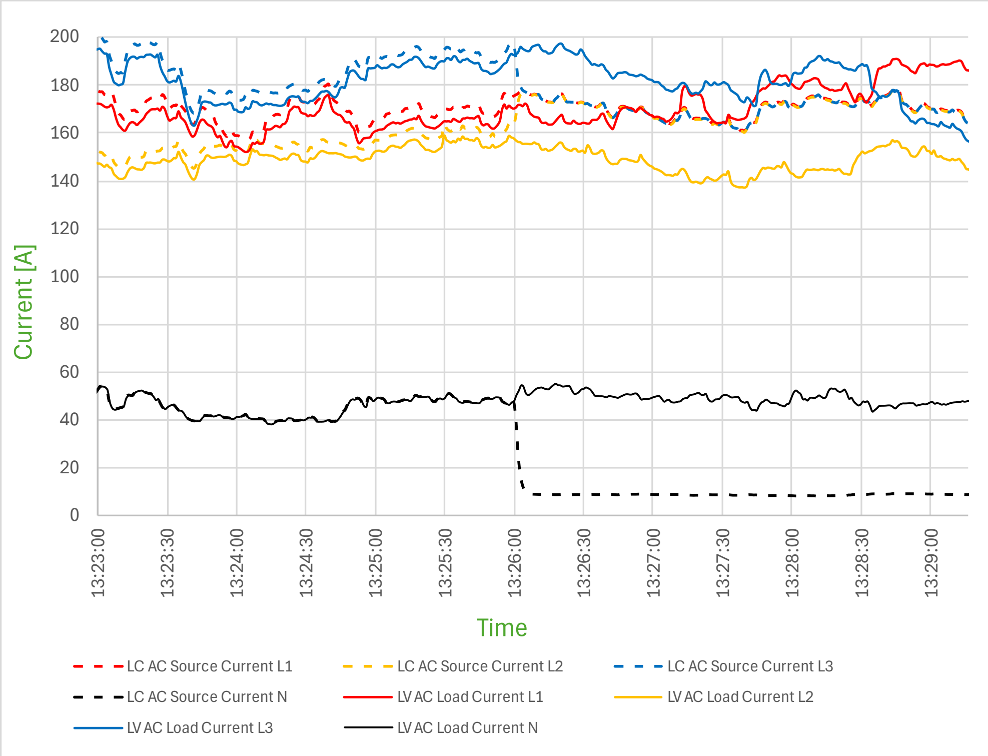


Figure 33 - Phase and neutral currents on the source and load side of the UPFC during the imbalanced load test performed on 30 May

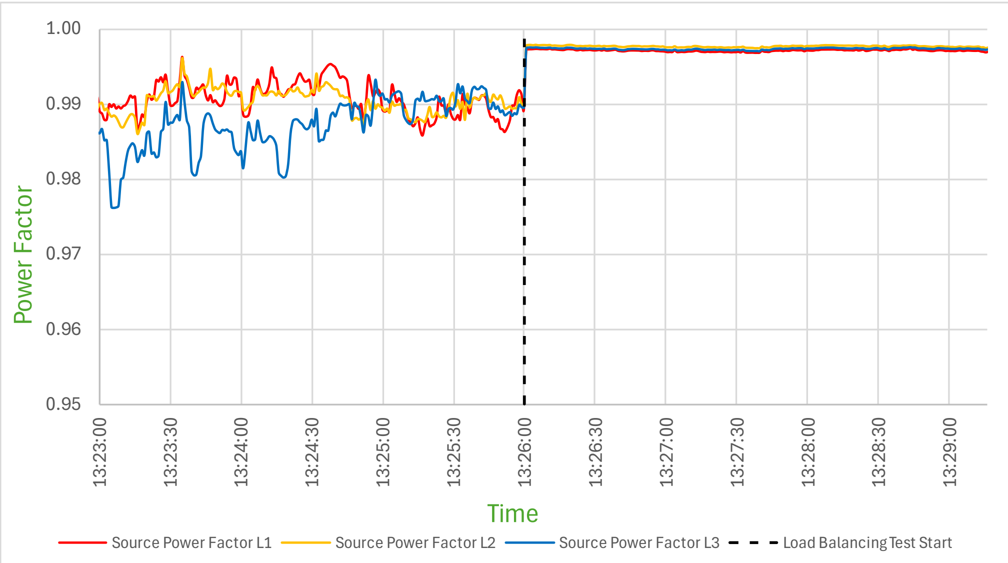


Figure 34 – Power factor on the UPFC source side during the imbalanced load test performed on 30 May

3.1.8 Conservation Voltage Reduction Test

Conservation Voltage Reduction (CVR) is a technique used to lower the voltage supplied to loads in order to reduce energy consumption while maintaining acceptable voltage levels for end-use equipment. The Unified Power Flow Controller (UPFC) plays a key role in implementing this by allowing precise control of the voltage on each phase. By dynamically adjusting the voltage set points, the UPFC can reduce or increase the voltage supplied to the load. This capability helps in managing the power drawn from the grid more efficiently, resulting in reduced active power consumption without affecting the performance of connected equipment.

The CVR test was performed between 06:45 and 08:30 on 11 October. The active power and reactive power along with the LV load voltage during the test are shown in Figure 35 and Figure 36 respectively. The test was performed by switching the voltage setpoints between 240V and 250V several times during the test and measuring any change in power both before and after an increase or decrease in voltage.

A scatter plot showing the relationship between the change in active power and change in voltage is shown in Figure 37, and the same for reactive power is shown in Figure 38. Each point on the scatter plot corresponds to the point in time when the voltage changes. The plot shows a consistent directly proportional relationship between the change in power and change in voltage. In other words, a rise in voltage results in an increase in power consumption and a fall in voltage results in a decrease in power consumption. The CVR factor which is defined as ratio of percentage change in active power to percentage change in voltage was found to have an average value of 1.06.

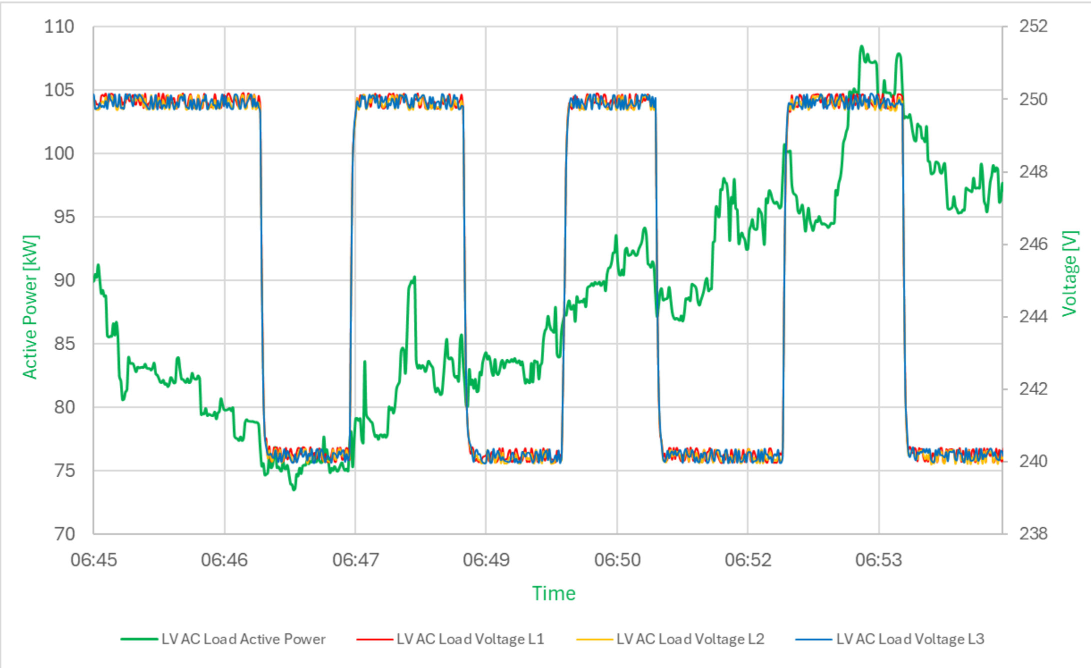


Figure 35 – LV AC load voltage and active power during the CVR test on 11 October

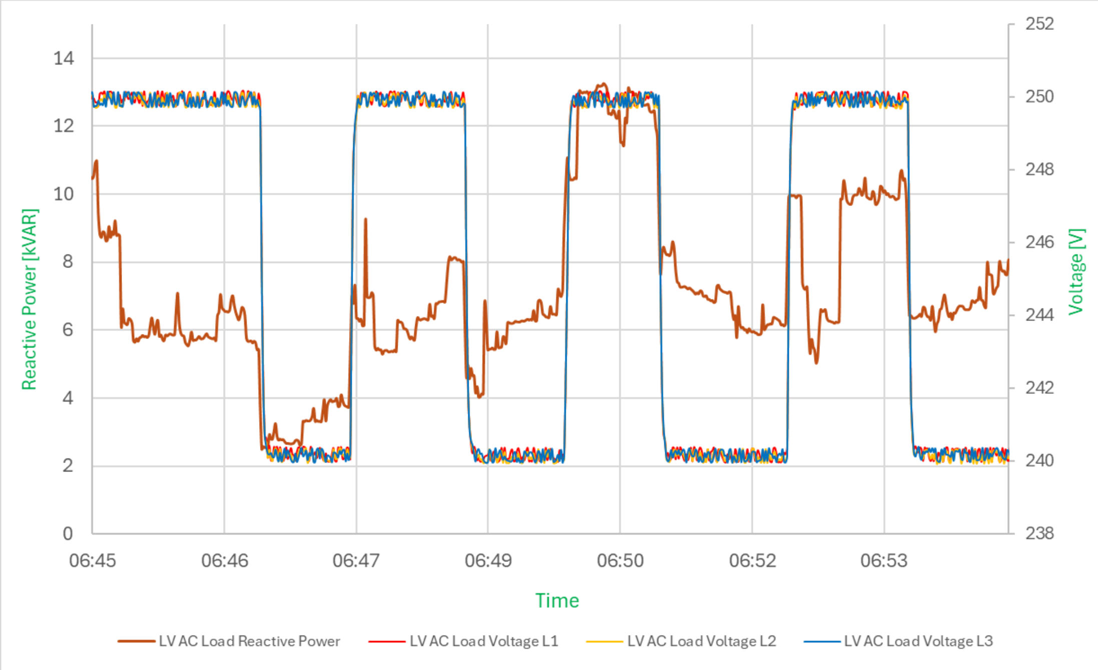


Figure 36 – LV AC load voltage and reactive power during the CVR test on 11 October

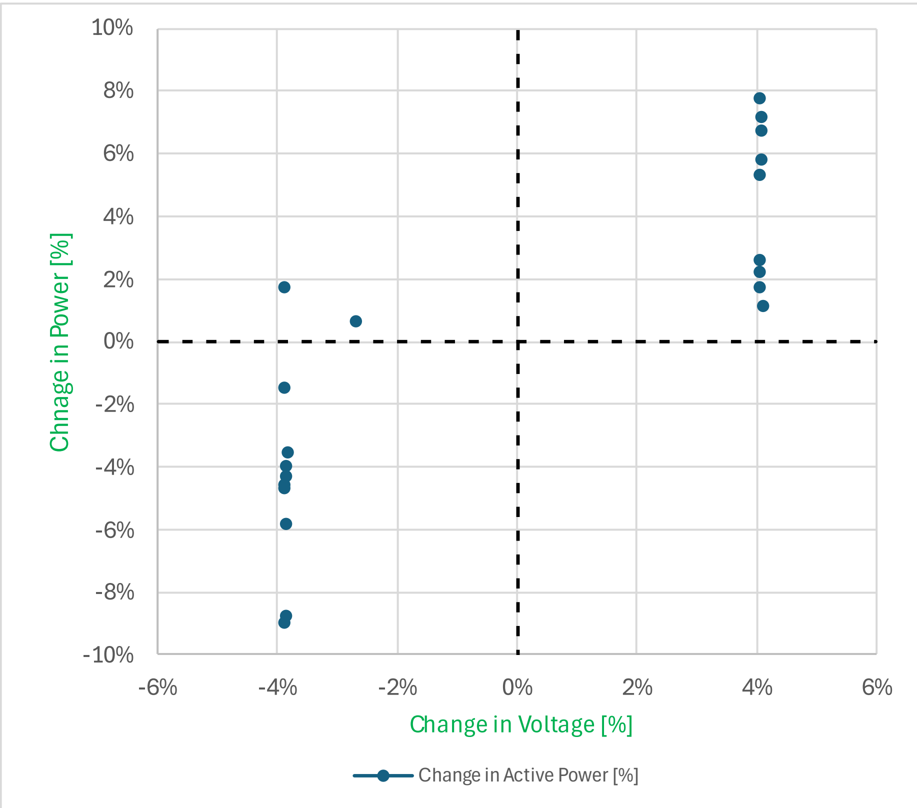


Figure 37 – Relationship between change in active power and change in voltage

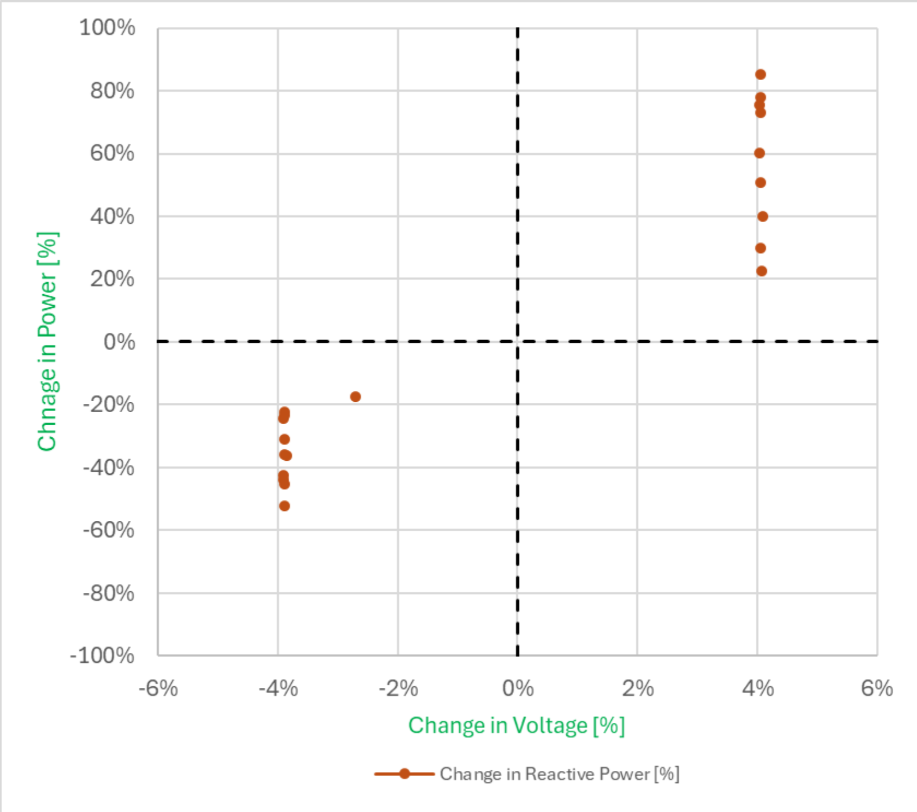


Figure 38 – Relationship between change in reactive power and change in voltage

3.2 LV Engine scheme 4 and 5 trial

The Falkirk Stadium site trials the performance of one LV Engine substations providing an LV DC supply to a single EV Charger, Figure 39. The LV DC cable from the substation to the EV Charger and the EV charger itself are owned by the customer (Falkirk Council).

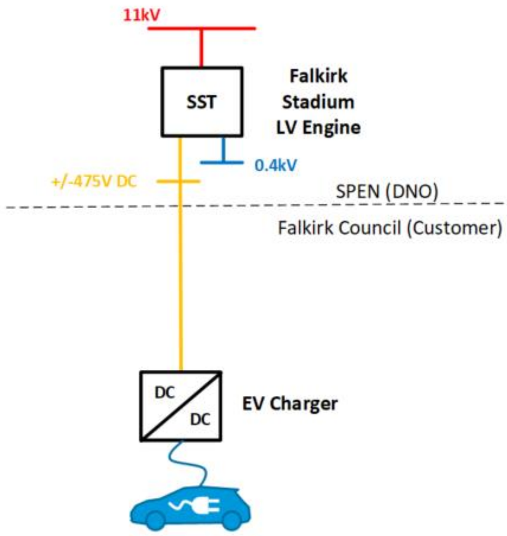


Figure 39 – Falkirk Stadium LV Engine network

This site is similar to the SST substations in Wrexham but with the following differences:

- The UPFC LV DC Load terminal is connected to an LV DC switchboard.
- The LV AC switchboard only supplies power to substation auxiliaries (lighting, protection, telecoms). It does not power a distribution network.

The UPFC provides efficient power conversion from the LV AC Source terminal to the LV DC Load terminal thus providing an LV DC supply to the customer's LV DC EV charger.

In order to assess the performance of the system, the UPFC LV DC Load power is compared to the UPFC LV AC Source power allowing the efficiency of the conversion process to be determined. The LV AC Source voltage is also analysed, before and during charging to examine whether source voltages are affected during charging. Short duration tests were carried out on 6 August 2024, Figure 40.

When the UPFC is not supplying LV DC Load, it draws around 1.7 kW of power from the source which is due to the idle losses resulting from control circuitry and auxiliary components within the UPFC and the substation auxiliary load. When LV DC power is being supplied, the average efficiency of the LV Engine system was found to be 92.5%. A comparison between the source phase voltages and the DC power supply patterns shows no significant correlation between the two quantities, leading to the conclusion that the use of DC power supply function within the LV Engine has no adverse effect over the source network.

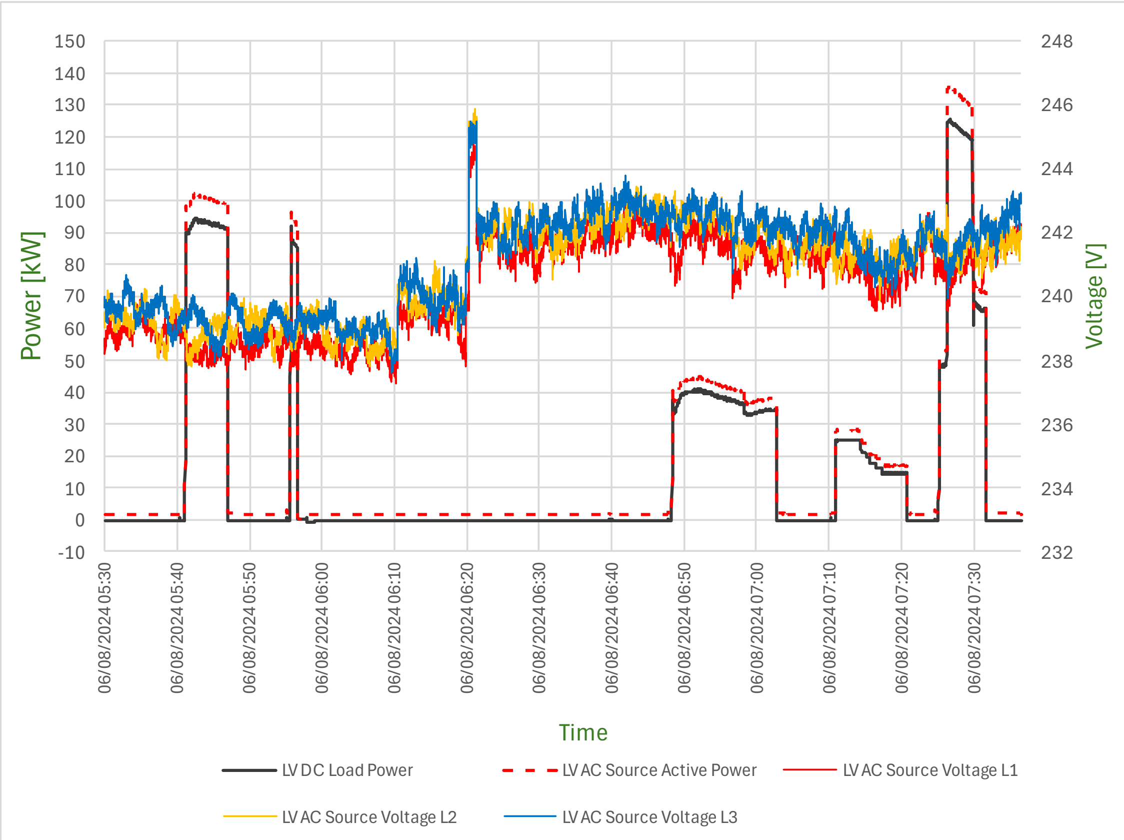


Figure 40 Performance of the UPFC when providing DC for EV charging

3.3 Operational Safety Requirements

Prior to any work on the UPFC, it is necessary to first isolate and ensure there is no stored energy in the UPFC or connected apparatus by carrying out the following steps:

- Isolate the UPFC
- Measure and discharge stored energy
- Test and prove not live

The following process is adhered to:

1. Isolate the UPFC from the LVDC switchboard by opening the switch-disconnector (isolation point 5).
2. Isolate the UPFC from the LVAC switchboards by removing the links (isolation point 2).
3. Isolate the UPFC from the incoming supply by opening, earthing and locking off the HV circuit breaker on the RMU (isolation point 1)
4. Ensure safety documents have been issued with further precautions on stored energy, reflecting the processes for proving not live.
5. After the UPFC isolation, the stored energy will be discharged automatically via the bleeding resistors internally fitted to the device, Figure 41. Measure the DC internal stored energy by using a multi-meter at the DC Bus Measurement Port on the UPFC front panel. In normal operation condition, the internal capacitor is charged up to 800V which is equal to 8V at the DC Bus Port (100/1 ratio). After isolation, the voltage is discharged internally (internal bleeding resistor), wait until voltage at the DC Bus Port is as close as to 0 Volt. (~3 minutes).

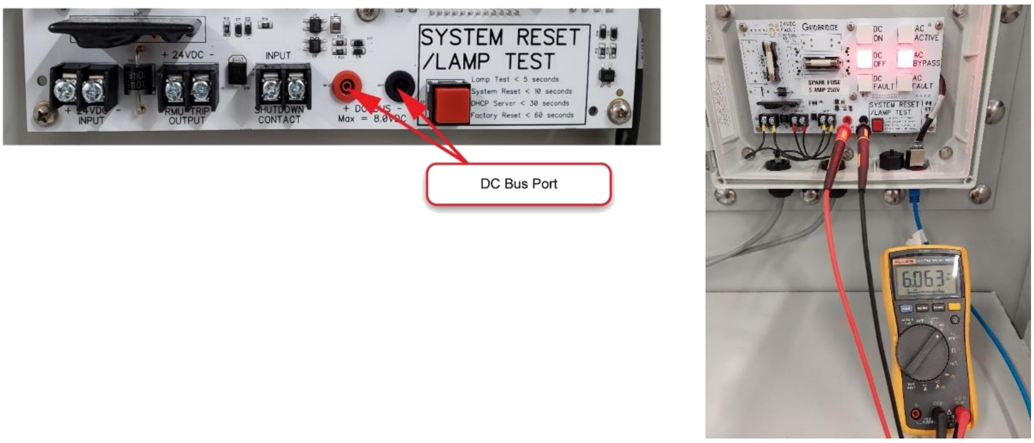


Figure 41 – Measuring the internal stored energy of the UPFC via the DC Bus Port

6. Use a discharge rod to earth the UPFC LV AC source, LV AC load and LC DC load terminals. Each phase can be discharged one at a time, keeping a connection to earth for 2s. Confirm the voltage at each terminal is discharged (almost zero) using multi-meter. If cables from the UPFC to LVDC and LVAC switchboards are traceable, then discharging and measurements can be carried out at the incomers of these switchboards, in this way there is no need to open the UPFC cable box front panels to

access its terminals. When discharging the stored energy, insulated rubber glove shall be worn at all times.

4 Performance compared to the original Project aims, objectives, Project Deliverables

LV Engine successfully delivered the functionalities which was originally aimed for LV Networks. Our Deliverable #6 demonstrate the performance of the solution in live network and how various smart functionalities can be used for more flexible and controllable LV networks. LV Engine generally achieved its original aims and objectives stated in initial submission as listed below:

Design and trial of the first UK grid connected SST for application within secondary substations

Three substations fully fitted with LV Engine solutions were installed and commissioned during the project. They have been operational at the time of writing this report. SST Topology 1 is the first of its kind in the UK, if not the world, that can provide hybrid LVAC and LVDC supply with smart functionalities targeted in LV Engine project. The detailed of manufacturing and installation is provided in LV Engine Deliverable #6.

Provide functional specifications and control strategies for deploying the smart functionalities which an SST can provide in different network conditions

Before the design phase started, we prepared a technical and functional specification of SST and its control methodology in the grid. This information is provided in LV Deliverable #2.

Compare the performance and functionalities of SSTs with those of conventional reinforcement and transformers fitted with OLTCs

In addition to SST substations, we installed a number of voltage regulating distribution transformers (transformers fitted with OLTC) to understand their performance and impact on our network. The learnings from those installation contributed to our understanding about VRDT technology which led to further deployments of the solution under green recovery fund. Nonetheless, the functionalities of VRDT and SST have been compared in LV Engine Deliverable #6 which shows superiority and wider functionality capabilities of SST Topology 1.

Provide technical guidance, policy documents, a cost benefit analysis methodology and tools for the intelligent selection of future secondary transformers to ensure the Business as Usual (BaU) adoption of SST technology

There have been significant learnings from live trial performance of the device which led to developing a computer model of the device and guidance for selection of the solutions. The use cases, and examples of cost benefit analysis were also developed and published in LV Engine Deliverable #7.

Provide functional specifications of a fit-for-purpose network design to inform the provision of LVDC supplies

We had extensive work on design of LV DC supply that included design and manufacturing LV DC switchboard, earthing requirements, operational safety requirements, the protection strategy. The technical specifications of LV DC switchboard and the LVDC protection strategy have been published on LV Engine website.

Demonstrate the protection of LV networks where power electronics are used

We carried out several protection studies on our trial networks to understand the requirements for network protection in presence of power electronic technologies. That contributed significantly to selection of SST Topology 1 design which has minimum impact on the existing LV protection arrangement.

Stimulate the SST market for future competitive production of this technology

We engaged with several stakeholders to promote LV Engine technology and encourage manufacturers and SMEs to consider this technology. This engagement took place through Power Electronics UK and Compound Semiconductor Application Catapult. Also, we had extensive engagement with UK manufacturers in one-to-one basis to share the learnings from LV Engine and opportunities for rolling out the solution. This effort took place as part of our plan to bring manufacturing of this technology to the UK with a specific focus on second generation of LV Engine solution.

Provide performance data together with the control algorithms to universities for further academic research and development

Our university partners, University of Strathclyde and University of Kiel, were involved in the project from start. In particular, we had extensive collaboration with University of Strathclyde in various network modelling, performance studies and testing. The data from the project can be requested via our website in future for further research activities.

Up-skill internal staff on power electronics technologies and applications within distribution networks and the value it can bring

Our engagement with internal staff during the project raised awareness on power electronic technologies and their applications. We carried out the following actions:

- Regular internal disseminations and discussions on developments of the solutions and designs
- Site briefing and performance demonstration for operation and field staff
- Training by manufacturer on site about maintenance and troubleshooting. This happened in practice by working alongside the manufacturer experts
- Conducting limited maintenance activities by our operation staff guided remotely by the manufacturer
- Training during Integration Testing conducted in Scotland when our staff attended the tests to become familiar with the technology and witness some of the tests
- Issuing and disseminating technical expression on safety requirements for operation of power electronic technologies

Knowledge dissemination to UK DNOs and the UK power electronics industry to facilitate the replication of the LV Engine solution across GB

Dissemination activities was in the core of our project delivery to raise awareness and share learnings especially with other DNOs, academics and power electronic communities:

- **Energy Innovation Summit**: We presented project learnings in Energy Innovation Summit since project started. Our participations were in form of presentations, discussions at our stands, videos, 3D models etc.
- **DNO workshops:** We conducted DNO workshops at key stage of project, especially design and live trial performance assessment, to have open and valuable discussions among ENA members.
- **LV Engine Website:** LV Engine progress reports containing the learnings from project gathered in each reporting period, also LV Engine videos were available on LV Engine website.
- **Conferences and Journals:** several workshop, conference papers and journals published in collaborations with our academic partners during the projects. Some of the conferences are CIRED, AC/DC IET, PowerTech and also publication in IEEE journals.
- **ENA working group:** In collaboration with our project partner UK Power Networks, we proposed a new ENA working group to publish learnings on power electronic technology in distribution networks. The ENA working group gathered learnings from various projects and published a new guidance on tests required for power electronics technologies.
- **Cigre and IEEE Webinar:** We delivered Cigre and IEEE webinars on LV Engine solution with academics, network operators, and manufacturing parties participated in the webinars.

Collaborate with our project partner, UK Power Networks, to develop a solution which can be adopted by all UK DNOs for BaU planning and operation of LV networks

Our collaboration with UK Power Networks was a great success in advertising power electronic technologies and also share the learnings between the two companies. Our collaboration provided the opportunity for us to openly discuss the development of the solutions in design and manufacturing stages. UK Power Networks, as part of their commitment to LV Engine, produced a report showing the business cases and opportunities of deploying LV Engine in their licence areas. This report, together with our other learnings from LV Engine, is essential for the roadmap to larger volume deployment of this technology as the evidence provided by two UK DNOs can trigger the competition in the market and support the future BaU adoption of the solution by optimising the final product cost.

LV Engine also successfully submitted all 8 deliverables as planned in the Project Direction:

Deliverable #1 - Technical specification of SST and functional specification of the LV Engine schemes' including relevant control algorithms.

Deliverable #2 - Detailed technical design of SST by the manufacturer and life cycle assessment.

Deliverable #3 - Manufacture SSTs for LV Engine schemes.

Deliverable #4 - Complete network integration tests.

Deliverable #5 - Establish the system architecture of LV Engine schemes.

Deliverable #6 - Demonstrate the functionalities of SST.

Deliverable #7 - Best operational practices of SSTs.

Deliverable #8 - Identify a trial site for replicating LV Engine solution within UK Power Networks.

5 Required modifications to the planned approach during the Project

LV Engine delivered the core functionalities intended originally in the full submission. However, two specific modifications applied to the project as listed below:

1. During our extensive market engagement in the first year of project (2018) when we were developing LV Engine technical specifications, we identified a risk that there can be some technical challenges in manufacturing the full power electronic Solid State Transformer or the final unit price of this technology cannot compete with conventional network reinforcement solutions. Therefore, in order to de-risk delivery of core functionalities and future roll out of LV Engine, we considered developing two SST products: SST Topology 1 and SST Topology 2 as explained in section 2.3. When project progressed in design and manufacturing, the aforementioned risk turned to an issue. For that reason, and to ensure project deliver the best value for money spent, we opted to focus on SST Topology 1 for the rest of project with no alternations to the core functionalities. The issues encountered during SST Topology 2 developments are as follows:

   - The existing semiconductor technologies will not result in a product that can be replicated for roll out. The highest voltage rating for Silicon Carbide Mosfets that were commercially available were around 2.0kV, that requires at least 4 modules to stack up in each phase for 11kV network interface. We spent significant time designing and testing the HV SST layout and practicalities in terms of installations on site. The final dimensions of this product and process required for site installation did not offer a solution that we can replicate after project completion. We believe higher voltage Silicon Carbide Mosfets will be available soon to the market that fundamentally change the design and size of this product.
   - SST Topology 2 was required to be significantly over-rated to accommodate the minimum fault current required for LV fuse protection arrangement. In order to avoid increasing the SST rating which contributes to cost of size of the unit, we initially planned to work on an IGBT built bypass converter that can only be in operation during fault for hight fault current provision. However, after further designs and tests, this option was proven not to be reliable.
   - The voltage impulse withstand of 75kV was a challenging requirement for connection to the 11kV networks. Our design already consisted of several units in series to allow connection to 11kV Power electronics.
   - Although the modular design approach could help the manufacturing and was essential for interfacing the 11kV networks, we encountered sever complexity when we consider the work required for the installation at the substation.

- The expected unit cost became excessively expensive than initially expected therefore the business case and market roll out opportunity become weak and not justifiable.
- A high impact and high probability risk was identified that continuing the SST Topology 2 development may result in project overspent and affecting project programme delivery time.

2. Our initial plan was to implement an LV network automation with controllable circuit breakers placed in linkboxes and LV switchboards in the substations. The aim was to change the network configuration to allow automatic capacity sharing at optimum times. However, we encountered a number of operational safety, cyber security and technology issues, which are listed below. Therefore, we opted to remove the remote-control function from the overall system architecture. Instead, the final LV Engine system architecture was able to monitor multiple devices using a smart communication hub architecture. The capacity sharing function was also demonstrated manually in a safe controlled procedure as reported in LV Engine Deliverable #6. Issues encountered are as follows:

   - Safety procedures for remote control of LV devices and establishing LV control room functions were not developed in SPEN in parallel with LV Engine project progress. Development of LV control room functionalities and organisational changes was not part of LV Engine scope of work and that requires extensive development which could have come with significant cost and time on LV Engine causing overspent and risk of non-delivery.
   - All the infrastructure related to recording and analysis of LV networks monitored data were built in SPEN's IT network as part of SPEN's BaU. This decision is partly due to much larger data volume communication and analysis is required for LV networks, compared to HV distribution networks for which data are captured and communicated to the real-time system (OT) infrastructure. Nonetheless, OT infrastructure holds the conventional remote-control functions which are well established in SPEN's control room for HV and EHV networks. For data monitoring and control at LV, even as a demonstrator, we had to create a bridge between IT and OT infrastructure which raised major cyber security issues. These issues could not be resolved only by LV Engine and even a stand-alone demonstration would have offered only little learnings that could not contribute to an enduring solution.
   - During the project, there were issues with access to Smart Meter data and using them in "near-time" to input to a remote LV voltage regulation function. Smart Meters are those used for energy billing purposes installed by energy retails company. The issue was mainly related to infrastructure, data pulling rate and SPEN's interfaces with the Data Communications Company (DCC).

- After extensive market research and technology assessments for Linkboxes automation products, we concluded that there are multiple issues that will impact the cost of trial while there was high chance of failure. Some of the issues included condensation impact on products, water ingress, poor communication reception, space required for fitting the products. We also exchanged learnings with our project partner, UK Power Networks, who encountered the same issues with the existing product in the market.

6 Significant variance in expected costs

The overall project expenditure was less than those initially predicted in the project. This underspent was mainly achieved by focusing on activities that will provide best value to customers and also fulfilling the original aims and objectives of the project. Table 4 shows the comparison between planned and actual expenditure.

Table 4 planned and actual expenditure comparison

Category	Planned Expenditure (£k)	Actual Expenditure (£k)	Variation
Labour	£1,756.72	£1,062.47	-40%
Equipment	£3,393.00	£2,578.66	-24%
Contractor	£1,839.98	£3,265.06	+77%
IT	£125.00	0.00	-100%
Travel and Expenses	£324.13	0.00	-100%
Contingency	£693.80	0.00	-100%
Other	£162.65	0.00	-100%
Total	**£8,295.28**	**£6,906.19**	**-17%**

The reason for variations to the planned expenditures are explained as follows:

Variation in Labour and Contractor expenditures

- LV Engine project was managed during the Covid 19 pandemic period where we had significant impact on staff availabilities followed by post-pandemic backlog of works within the business for delivery of mainstream work. For that reason, and in order to avoid any further impact on project programme, we relied on all resources that we could attract to the project including external contractors. That resulted in variation in the planned expenditure on Labour (reduction) and Contractor (increase). The following assumptions have been considered in calculating actual costs:

    - All the actual “Travel and Expenses" costs have been included in the actual “Contractor” costs

    - The actual cost against category “Other” (which was mainly allowed for project auditing) have been included in actual “Contractor” cost.

  On that basis, the variation to the planned labour cost was -40% whereas the variation to “Contractor” + ”Other” + ”Travel and Expenses” expenditure was +40%. <u>It should be noted that the variation to summation of Labour and Contractor costs is +6%.</u>

Variation in Equipment expenditures and Contingency

- As explained in section 5, we came to conclusion that continuation of SST Topology 2 manufacturing and also LV automation are not best value for money in this development, therefore the total actual expenditure in the equipment category is around £750k less than initially planned. This decision also allowed us to save the £693.80k allowance we had initially considered for contingency, otherwise the development of low TRL technologies that we avoided, could have costed beyond the planned allowance for Equipment plus Contingency.

  It should be noted that the actual cost of all "IT" equipment has been included in the actual "Equipment" cost. <u>On that basis, the variation to "IT" + "Equipment" expenditure is -27%.</u>

7 Updated Business Case and lessons learnt for the Method

7.1 Business case

LV Engine provides new technology to solve voltage, thermal and imbalance constraints in LV networks. LV Engine may be selected instead of conventional reinforcement solutions such as new substations or other emerging technologies such as voltage regulating distribution transformers. LV Engine use cases, as demonstrated successfully in the live trial, can be one of the following:

- Addressing Undervoltage and Overvoltage Issues

  One of the primary functions of the LV Engine is its ability to solve undervoltage and overvoltage issues by precisely controlling the voltage on each phase individually. Locations with high uptake of PVs, long LV feeders and also rapid demand growth due to connection of heat pumps and EV chargers can benefit from voltage control capabilities.

- Balancing imbalanced Loads

  Imbalanced loads are a common challenge in LV networks, often caused by single-phase loads distributed unevenly across three-phase systems. This imbalance can lead to inefficiencies, overheating, and reduced transformer lifespan. LV Engine's ability to make imbalanced loads appear balanced to the distribution transformer (or upstream network) can be useful for better utilisation of transformer and cables during peak time.

- Capacity sharing between substations

  LV Engine solution can be used for capacity sharing between neighbouring substations by using voltage control capabilities. The fine voltage control and ability to adjust the power level allows more flexibility for capacity sharing. Capacity sharing can be considered between two substations where headroom is available if one is underutilised, or the two substations are supplying complementary load profiles e.g. one is supplying a residential area and the other supplies more commercial customers.

Any of the uses cases mentioned above can be achieved in two different installation arrangements, as shown in i) installing within an LV circuit or ii) installing at the substation

Application in substation

(Radial or interconnected network)

Application within a circuit

(Radial or interconnected network)

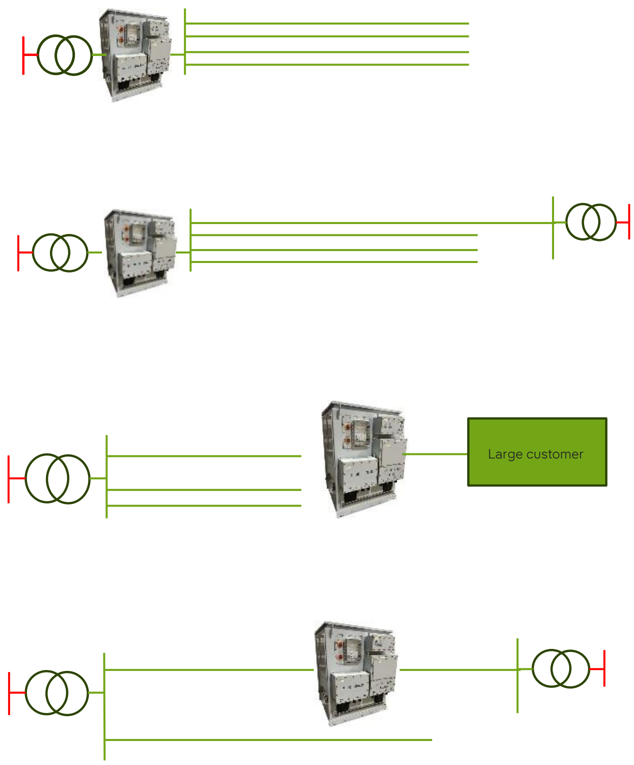


Figure 42 different installation arrangements for LV Engine solutions

LV Engine Deliverable #7 provides a techno-economic assessment for an example LV network where several issues and scheme may be required to resolve the thermal and voltage issues.

The business case prepared initially in the LV Engine Full Submission is still largely valid and show strong opportunities for technology roll out across GB. Counterfactuals still valid against conventional network reinforcement: upgrading cable circuits and new secondary substations.

The comparison between Future Energy Scenarios (FES) used in 2017 and FES 2024 shows the average difference between residential peak demands forecasted in FES 2017 and FES 2024 for the years from 2020 to 2040 is within 5%. The key difference is that FES 2024 shows slower electrification up to 2037 (compared to FES 2017) however larger electricity peak demand growth beyond 2037. It should be noted that we also considered demand reduction as forecasted by FES 2024 by customers' peak shifting services.

On that basis the total benefit expected from LV Engine deployment across GB has changed moderately from £285m to £313m by 2040.

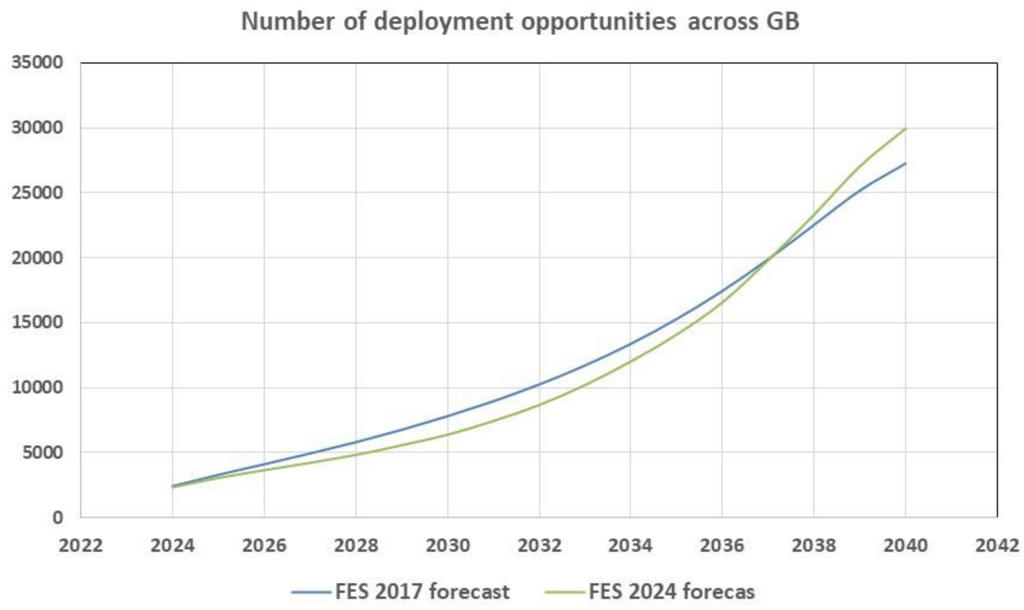


Figure 43 LV Engine deployment opportunity across GB

7.2 Lessons learnt from the LV Engine method

Learnings gathered from LV Engine have been extensively reported in progress reports and project deliverables, however, some of the key learnings are as follows:

Power electronic topology

After significant topology optioneering, studies and benchtop testing on possible SST Topologies, we concluded that the UPFC topology connecting to the LV (either within a substation or within an LV circuit) can be the most efficient and reliable topology to deliver functionalities intended in LV Engine. The following reasons can support this decision:

- *Performance during the fault* – This topology provides the same level of fault contribution to the faulted LV network as conventional transformer, eliminating the issue of low fault current provision by power electronics so that the solution has no impact on the existing LV fuse protection.
- *Improved efficiency* – The overall efficiency can be up to 99% with the UPFC design as the power electronics do not need to supply all the LV demand and only operates to provide the system services when required. This will improve the efficiency and life-time losses significantly as compared to SST Topology 2, or an LV back-to-back converter which their efficiency is usually lower than 97%.
- *Smaller power electronics power rating* – For the same reason explained above, nominal power capability of the power electronics can be reduced significantly. This reduces the design complication, overall system cost and cooling requirements which ultimately contributes to lower maintenance cost.
- *Bypass possibility* – The UPFC design allow fail-safe bypassing the power electronic unit when it is not needed or if there is any issue when power electronic components.

- *Smaller dimensions* – The lower power electronics power rating, higher efficiency and capability to bypass during the fault conditions contribute to a more compact physical layout design compared to other SST topologies.

Design and simulation studies in advance

After selecting our trial sites, we carried out several detailed studies especially assessing the protection system and general performance of the network showing before and after LV Engine deployment solution. Those detailed studies significantly helped us to better understand the expected grid performance and identify potential issues in advance of manufacturing and trials. We strongly recommend that before implementation a study phase carried out to understand the expected performance and impact of LV Engine solution. There are several functionalities (voltage control, cancelling imbalance load, capacity sharing and power factor correction) that LV Engine offers that need to be evaluated based on the specific networks and expected demand/generation growth.

Manufacturing and testing issues

While most of the tests passed the requirements, we encountered number of issues during factory tests:

- *Bypass system* – As stated in the previous reporting period, the solid state relay (SSR) designed to bypass the device did not fulfil the initial factory tests. Consequently, ERMCO team redesigned it, built the new SSR and tested in various stages. The second prototype also did not pass the tests due to higher speed of processing required to detect the overload conditions activating SSR. However, the third attempt for the design was successful and final build was established.
- *Thermal issue* – The operation of SST under full load resulted in an uncontrolled temperature rise in the isolation transformer in the DC/DC converter. Therefore, a new engagement with the DC/DC transformer supplier started in parallel with new market research for similar transformers. Eventually, a new design for the transformer with extra cooling pipes was agreed with the original supplier. They have now provided their prototype for testing. The initial tests confirmed the new design is expected to fulfil the thermal requirements. The final product was shipped to ERMCO in March 2023 to be fitted in the final SST product.
- *DC-link failure* – During various factory tests, DC capacitors forming the internal DC-link, failed. The diagnosis was that the presence of excessive DC ripples resulted in extra thermal stress on the capacitor and consequently failure. A new type of capacitor with better specifications was identified and purchased. The capacitors have a cubical shape whereas the original capacitors were cylinder shape, therefore, a new arrangement for fitting in the enclosure was also developed.

Maintenance

Power electronic technologies are relatively new for applications in LV public networks. While there are recommendations from manufacturers on their product's expected lifetime and maintenance requirements, there are not adequate field data to conform these requirements.

We carried out annual maintenance on LV Engine power electronic solution, our key learning was that the dust accumulation on fans and internals of the device was not significant in brick-built substations. The device internal did not need major cleaning in these substations which was in line with initial manufacturer recommendation. However, for the unit that we had installed within a Glass Reinforced Plastic (GRP) housing we noticed significant deterioration to the heat sink at the back of the unit.

The GRP housing was designed for provision of indoor environment, however, in the extreme weather condition that we experienced during a number of storms, rain had been blown into the substation from the GRP enclosure's mushroom-shape roof. The water ingression to the substation eventually found its way to the louver at the side of power electronic unit which then sucked in by the fans and significantly increased the humidity on heat exchangers' surface. That consequently deteriorated the copper surface of the heat exchanger which reduced their overall lifetime although they were still operational after necessary cleaning carried out.

Need for voltage management at LV

Learning from analysis on voltages reported by energy Smart Meters suggested that LV Networks are generally/historically operated at higher bound within statutory limits (230V +10% %-6). This may introduce two key issues:

- Increase the risk of overvoltage during off peak time especially in the area with uptake of photovoltaic technologies.
- Likelihood of impacting customers annual consumption resulting in higher annual energy bill. Customers may have voltage dependent appliances that in higher voltage consumed more.

We recommend, where possible and designs allow, local LV voltage optimised to a lower level with statutory limits. LV Engine solution and VRDTs can be suitable technologies for this purpose especially if control strategy can include voltages reported by energy Smart Meters and LV monitoring solutions.

Smart Hub – testing

One of the challenges was for the team to test the smart hub firmware (router) prior to commissioning on site. LV Engine equipment was designed and developed by different vendors located in different countries. Therefore, it was physically impossible to give the equipment to the router vendor, Australian based, to run their factory tests and ensure communication with devices and protocol conversions are working as per design.

In order to facilitate the test, we established VPN channels from vendors' offices to the router supplier offices to allow live communication of the devices with the router. In this way, the router supplier could establish the full I/O schedule communication with each device i.e. UPFC, LV Circuit Breaker and Local Control System. After that confirmation, we had to confirm those IOT messages can receive by SPEN's FieldOnline which uses Azure services.

In order to mimic the SPEN's Azure environment, router supplier created an Azure environment with the same settings as SPEN's Azure to which SPEN's IT team was appointed as Listener via service bus client. In this way SPEN's IT team could see the data points communicated from UPFC, LCS and LVCB vendors to router supplier in IOT messaging format. This data then routed in SPEN IT infrastructure to data historian and LView platform confirming an end-to-end pre-trial test. All these tests were happening while devices where in vendors premisses in their respective countries and in different time zones. Figure 6 show a general set up for pre-trial testing.

Several issues were encountered during these tests that resulted in firmware updates by all the vendors. This exercise was successfully de-risk the issues that could arise during commissioning where vendors were restricted with time and access to the equipment in the substation.

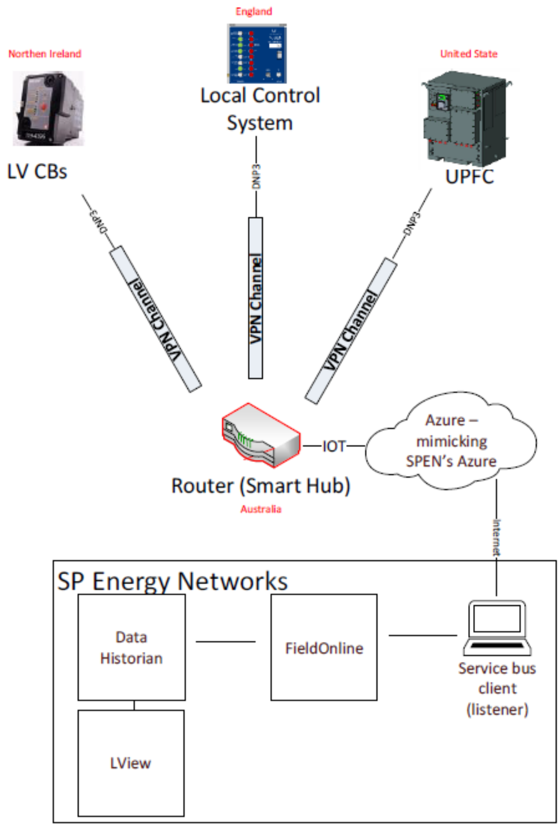


Figure 44 Test set up for LV Engine Smart Hub

Safety requirements

Power electronics devices and LV DC technologies that contain capacitive equipment maintain electrical charge even when they are isolated. To avoid any risk of electric shock or danger from stored energy, a procedure was developed and published as part of operational technical guidance. The following three steps should be taken prior to any work on LV Engine power electronics technologies:

- Isolate the device
- Measure and discharge stored energy
- Test and prove not live

This procedure should be clearly communicated with operation staff with copies visible at the substation.

Troubleshooting and internal databases

LV Engine SST Topology 1 (UPFC) captures and record extensive datapoints (electrical parameters, temperature at various internal points and alarms) for off-line interrogation, troubleshooting and performance analysis. These databases were used during laboratory testing and also live trial helping the team to effectively troubleshoot the event. That was particularly helpful during project as the manufacturing team were based in the United State in different time zone, so we could share the databases with them to be examined for providing remote technical supports.

HMI control and control cabinet LED display

We recognised that operation staff should have adequate access to information locally to carry out any control settings or network defect. LV Engine substation is different from conventional secondary substations with new technologies and new operation procedures. It was therefore necessary to ensure our operation staff, in addition to training, can use information from various displays in the substations to understand real-time status of contacts, alarms, and power electronic technologies. This was also crucially important in the substation with DC supply where we had various contacts and inter-tripe schemes as part of protection strategy.

To facilitate this, power electronic technology was fitted with a Human-Machine Interface (HMI) to show alarms and allow operation staff change the control settings. Also, we designed a local control system with various LEDs that we could display the status of DC circuit breakers, HV circuit breaker and leakage relays. Having this information available on various displays, helped significantly our operation staff to adopt the technology.

DC protection

DC protection was one of the challenging developments in the project. We ran extensive studies following with laboratory testing to establish our protection strategy. Due to the use of power electronic based rectification, the UPFC DC output cannot provide sustained fault current in excess of its rating (158kW or 166A). Therefore, typical LV AC protection schemes based on overcurrent devices such as fuses or thermo-magnetic devices in moulded case circuit breakers (MCCBs) are not suitable for this application. However, the UPFC automatically switches off the DC supply if it experiences any current beyond its rating.

SPEN's LV DC switchboard where a DC MCCB provides point of isolation between customer's cable and LV DC switchboard. The MCCB is fitted with a shunt trip release that may be triggered by one of the following conditions:

- Undervoltage on the positive pole, triggered by a control relay in case of loss of voltage i.e. DC supply switches off
- Undervoltage on the negative pole, triggered by a control relay in case of loss of voltage i.e. DC supply switches off
- Earth current leakage detection by a Residual Current Monitor (RCM), in case there is any current flowing between the DC mid-point and Earth.

The full details of protection strategy have been provided in LV Engine deliverable #3.

DC metering

DC metering as part of the DC customer connections created a number of challenges. The conventional CoP5 metering standard, suitable for 3 phase AC customer, could not be acceptable for the DC energy metering purposes. We considered a number of options and engaged with energy retail companies as well as Elexon that explore potential solutions.

Condition 20 of the Distribution Licence Standard Conditions requires the licensee to comply with the Balancing and Settlement Code (BSC) and the Retail Energy Code (REC). All metering equipment shall comply with or exceed the relevant BSC Code of Practice (CoP) (or where no CoP exists, Schedule 7 of the Act. The BSC will require modifications to allow the introduction of LVDC settlement metering. For example, the term Active Power is described as the product of voltage and the in-phase component of alternating current. Another example is the referencing of voltage transformers (VTs) and current transformers (CTs) which are used in AC metering but not DC metering where shunt resistors and hall effect sensors are used.

While there are regulatory challenges for an established DC metering, we proceed with technology research and other relevant standards that can be used or DC metering. IEC 62053 generally is to most relevant IEC standard for AC metering. The IEC 62053-14 is new issue for specifically DC metering, but it was released as a stable standard in 2025 which was very late within LV Engine project lifetime.

Based on the lack of standards and regulatory issues, we decided to fit the conventional AC metering arrangement, by fitting CT metering within the LV cable box of the distribution transformer which measures overall AC and DC total consumptions. As a results, our substation at Falkirk where DC is trialled, has been a dedicated substation for only one customer.

7.3 LV Engine updated specifications

Base on successful trial and learnings gathered from manufacturing and live trial, we updated the technical power electronic technical specifications to emphasis on essential functionalities that would be required. These modifications especially targeted to reduce the unit cost and make the LV Engine solution more competitive to conventional reinforcement. The modifications to the technical specifications aim to achieve three key elements:

- **Reduced Unit Cost:** While we successfully demonstrated the LVDC supply during live trial, we learnt that lack of an approved DC energy metering arrangement will significantly affect the chance of large volume deployment of LVDC technology. For that reason and enhancing the chance for LV Engine future roll out, we decided to focus on functionalities it can provide to AC network only. Also, the learning from field trial indicated that some of the functionalities can be modified or reduced, this will have direct impact on rating of power electronic technology modules which eventually reduce the cost of the unit.

- **Reduced maintenance cost**: LV Engine power electronic technology used liquid cooling system that adds to cost of inspection and maintenance, as time to time the reservoir needs to be checked and topped up with the coolant which is a simple process. The main cost is the labour cost as it requires in person attendance of staff.

However, in case of any failure in water pump and pipes, the repair cost can be significant.

- **Reduced the device dimensions**: The size of power electronic unit is around 120 cm (D) x 130 cm (W) x 160 cm (H), which we can be fitted into many substations. However, any smaller size unit can reduce the potential cost of land, enclosure and more chance of deployment in smaller size substations. Considering the elimination of DC supply and modifications to some of functionalities, the LV Engine next generation is expected to be smaller than the unit trialled during the project.

Key parameters in the new technical specification are listed in Table 5, other specifications are still valid in accordance with those stated in LV Engine Deliverable #1.

Table 5 Updates to LV Engine SST Topology 1 (UPFC) technical specifications

Parameter	Specification
Rated Power	500kVA
System	3 phase AC + Neutral
Input Voltage normal operating range	230V +/- 15%
Extreme overvoltage condition	+/-18% for 3 sec bypass, then trip the supply
Output voltage range	230 -6% +10%
Voltage regulation per phase	+/- 10V per phase Priority 1
Controlled power flow and capacity sharing services	Supported within the preset power flow and voltage boundary by the operator – Priority 1
Imbalance load correction	Maximum 30% Priority 2
Power factor correction	0.95 to Unity at rated power Priority 3
DC supply	Not required
Rated current	725A at nominal voltage
Maximum temporary overloading	850A at 85% of nominal voltage then bypass
Service conditions	-25°C to 40°C
IP rating	IP64 (for power electronic section)
Voltage and power flow control accuracy	+/- 1%
Overall size	Maximum 75% of original LV Engine
Application location	Within the substation or LV circuits outside substation
Bypass functionality	Manual by the operator or automatic following over current
Short circuit withstand	Similar to Distribution Transformer (15kA)
HMI	Similar to LV Engine Gen I
External communication	DNP3 Master and Slave
GUI	Web browser with dedicated IP for local connection.
Cooling system	Forced air cooling, no liquid cooling is allowed

7.4 IPRs

The following IPRs have been recorded during project delivery.

IPR	Owner	Type
Project concept	SP Energy Networks	Relevant foreground IPR
Project use cases	SP Energy Networks	Relevant foreground IPR
General technical specification of SSTs presented in LV Engine Deliverable #1	SP Energy Networks	Relevant foreground IPR
High level technical specifications of SST Topology 1	SP Energy Networks/ERMCO	Relevant foreground IPR
High level technical specifications of SST Topology 2	SP Energy Networks/ERMCO	Relevant foreground IPR
LVDC protection design of network	SP Energy Networks	Relevant foreground IPR
Detailed design of SST Topology 1	ERMCO	Relevant foreground IPR
Detailed design of SST Topology 2	ERMCO	Relevant foreground IPR
Technical requirements for smart hubs and communication I/O schedule	SP Energy Networks	Relevant foreground IPR
Performance analysis and data presented in Deliverable #6	SP Energy Networks	Relevant foreground IPR
Detailed design of trial sites	SP Energy Networks	Relevant foreground IPR
Commissioning method statement	SP Energy Networks	Relevant foreground IPR
Network integration testing and data presented in Deliverable #4	SP Energy Networks	Relevant foreground IPR

IPR	Owner	Type
Technical specifications of LVDC switchboard	SP Energy Networks	Relevant foreground IPR
High level factory testing requirements of SST Topology 2	ERMCO/SP Energy Networks	Relevant foreground IPR
Detailed factory testing of SST Topology 2	ERMCO	Relevant foreground IPR
Detailed manufacturing process of SST Topology 1	ERMCO	Relevant foreground IPR
Earthing design of AC/DC systems	SP Energy Networks	Relevant foreground IPR
System architecture design for LV Engine performance monitoring	SP Energy Networks	Relevant foreground IPR
LV Engine site selections methodology	SP Energy Networks	Relevant foreground IPR
Smart Hub firmware detailed development	Avara	Relevant foreground IPR
New technical specifications	ERMCO/SP Energy Networks	Relevant foreground IPR

8 Lessons learnt for future innovation Projects

LV Engine was a complex and multi-disciplinary project which required managing and developing scope for different project partners. Running projects in this scale enhances the knowledge and skillsets of all the project partners which can eventually contribute to similar technologies and development in the UK. Some of the key learnings that can be applicable to other innovation projects can be listed as follows:

Market engagement

Early market engagement is very important when development of a new technologies is intended. This allowed identifying the manufacturing challenges and project risks and clarify SPEN expectation from the project at early stage before procurement. We engaged with at least 8 manufacturers prior to procurement. That engagement informed us to make decision for pursuing two SST topologies in parallel for de-risking LV Engine project delivery.

Project Partner selection

Complex innovation projects, similar to LV Engine, requires strong and flexible project partners for manufacturing and designing the solutions. The project partners need to offer flexibility during scope delivery, resilient to unknowns and also offer some financial strength for investing in the development stage in return for the opportunity of being in the leading seat for designing and manufacturing a new product. We decided to select our manufacturing partners through competitive procurement process with detailed assessment on technical capabilities and financial investment motives. The tender process was carried out after we developed our detailed technical specifications, running preliminary studies and answered some unknowns that could have impacts on partner's scope of work and technical requirements.

We believe that competitive tendering, after detailed technical specifications development, will be more likely to offer better value for money, however, procurement can be time consuming process and should be taken into account during project programme development. The other benefit of competitive tendering is to raise awareness and opportunity for the new product in the market. Therefore, it is likely that some manufacturers who have not been successful in the tendering process, start developing the solution as one of their strategic development products using their own internal investment.

Manufacturing and testing issues

For new product development that requires extensive factory testing on a prototype, we strongly recommend building number of prototypes before final field unit manufacturing. Having 3 or 4 prototypes will allow parallel factory testing, especially if unit needs to be sent to an independent laboratory testing (e.g. short circuit withstand tests). Also, building multiple prototypes will inform the blueprint for the assembly of the final field unit manufacturing and assembly. This can potentially save significant delay and human mistakes that may happen during manufacturing.

Network integration testing

Integration testing for an innovation solution in which different vendors are providing key equipment is an essential development stage to ensure the overall solution functions as designed. The integration testing should adequately represent the final set up and operating conditions in the live trial to ensure minimum issues when the solution is part of the electricity system. LV Engine project significantly benefited from the network integration testing carried out in advance of live trials. There were several issues identified and rectified by the vendors based on what we learnt from pre-trial laboratory testing. That therefore helped a smooth installation and commissioning at our trial sites.

Site preparation and commissioning

We decided to carry out all the site preparation works in advance of units arrival to the UK. Our site design work was conducted in parallel with LV Engine equipment design and manufacturing to ensure the site design and device design are compatible. We believe that in advance site preparation helped us to be more efficient at the time of installations as there were fewer activities to be managed at the time of installation compared to full site preparation, installation and commissioning.

We also dedicated adequate time for staff training in advance of installation and commissioning, by reviewing the site designs, commissioning method statements and safety requirements. The well in advance engagement with staff (even external contractors) was certainly effective for a smooth installation and commissioning.

UK manufacturing

We believe UK manufacturing strategy should be consideration from start of project as one of the criteria for assessing the potential manufacturers especially for a newly developed device. The UK manufacturing and technical support growth can be a key enabler for the rolling out the solution. The manufacturer overall UK presence and growth strategy should not be dependent on the large volume order of the solution as this will be interdependent situation that would cause the roll out a failure.

Maintaining the trial site operational

The trial sites in innovation projects ideally need to stay live even after innovation project completion. This will enhance the learnings from the solution and inform better roll out planning or any update to the technical specifications for next generation of the solution. However, the funding mechanism for innovation projects (e.g. NIC funding) may not allow the ongoing operation and maintenance cost of the solution, hence, network operators may consider decommissioning the trial site. Ideally, a budget should be considered/approved for inspection and maintenance within the project that would be accessible by the network operator beyond project completion to maintain the solution within the corresponding regulatory period.

Unit cost valued engineer

For highly innovative projects, similar to LV Engine, the initial prototype may be overdesigned or not perfectly valued engineered, to allow the headroom for unknowns during live trial site tests. As a result, the product under trial may not be the most cost competitive solution although the technology readiness level can be 8 or 9. The value engineering and cost optimisation may be required for the second generation of the solution with fresh market research on supply chain if the equipment is built up from various components. The sub-system components used in complex long-term projects, like LV Engine, may not be the cost effective and market lead anymore after project completion. Therefore, a fresh supply chain optimisation can have significant impact on final unit cost of the solution enabling faster roll out of the technology.

De-risking trial Site selection

The sites earmarked for the trailing the solution may be impacted due to connection of new customers, assets failures etc that make that trial site not suitable for demonstrating the innovative solution. For example, one of the trial sites selected for LV Engine demonstration had to be used to connect the new LV commercial customer. We therefore had to equip the site with transformer and LV switchboard 2 years in advance of LV Engine equipment installation. However, because the detailed layout of the site was ready well in advance, we managed to do initial phase of installation in accordance with LV Engine layout, provide the supply to the customer, and then two years later with a short period outage management install the full LV Engine solution.

In general, we recommend that site designs are completed as soon as possible and understand flexibility in the design if site circumstances change. Also, we strongly recommend having alternative sites planned in advance to be prepare for replacing the target sites in case original site becomes unviable.

Collaboration with another DNO

The collaboration between SP Energy Networks and UK Power Networks in exchanging knowledge on two sister projects, LV Engine and Active Response, was very useful. Both parties had different issues during design, manufacturing and trial sites that was openly discussed on a regular basis. We also collaborated closely in identifying trial sites of power electronic solutions in each other license areas as part of deliverables on our projects. This close collaboration apart from de-risking some of the technology development, can increase the chance of rolling out solution.

9 Project replication

The Network Licensee should provide a list of all physical components and knowledge required to replicate the outcomes of this Project, also showing how the required and, where relevant, newly generated Intellectual Property can be accessed by other GB Network Licensees. The Network Licensee should also include details of the anticipated business-as-usual costs of replicating the outcome of the Project.

In order to replicate the LV Engine solution, the following design, software and hardware will be required, as a minimum. Some of these requirements may be tailored specific to the network operator organisation policy and process.

It should be noted that based on our learnings, and our plan for project replication, we have decided to remove the LVDC supply from project replication at this stage. Nonetheless, the information below includes DC technology in case this information is required.

9.1 Site Design

The following information may be required for the site design:

- **Site selection**: Based on the criteria and business case provided in Section 10 and in LV Engine Deliverable #7.

- **Site design:** Electrical site design, substation layout, safety requirements are provided in LV Engine Deliverable #3.

- **System architecture design:** IT System design can be specific to the network operator; however, adequate guidelines have been provided in LV Engine Deliverable #5.

9.2 Hardware

The following hardware are essential for replicating LV Engine solution.

- **Distribution Transformer** – This is a conventional distribution transformer, as per specification of network operator, providing HV/LV voltage conversion. (If solution is be deployed in the substation)

- **HV Circuit Breaker** – This is a conventional HV circuit breaker (also known as ring main unit), as per specification of network operator, for isolation from HV networks. (If solution is be deployed in the substation)

- **SST Topology 1** – This is UPFC topology that can provide several functionalities as explained previously in this report. We recommend using the updated specifications, see Table 5, which reflects the learnings from trial site.

- **LV AC Switchboard** – This is conventional LV Switchboard, as per specification of network operator, providing isolation from LV outgoing circuits.

- **LV DC Switchboard** – This is conventional LV DC Switchboard, as per specification provided by LV Engine project, available on LV Engine website.

- **LV Engine local control system** – This is cabinet designed to house the SPEN router and show the contacts, mainly for LVDC scheme, in the substation.

- **Protection strategy** – The overall protection strategy is provided in LV Engine Deliverable #3.

9.3 Software

Graphic User Interface (GUI)– We used a GUI for communicating with UPFC and downloading the databases and troubleshooting, a screenshot of the GUI is shown in LV Engine Deliverable #3.

Power system software – We recommend that steady state system studies to understand the impact of the LV Engine solution as part of design stage activities. A conventional power system tool is required to carry out these studies. A proposed model, representing the behaviour of UPFC in steady state, is proposed in LV Engine Deliverable #6.

9.4 Unit cost

As explained in section 7.3 the technology developed during LV Engine project needs some modifications to be more attractive and competitive to conventional reinforcement solutions. The unit cost for the existing power electronic product is around £170k for very low volume deployment and without any modifications. However, considering the new technical specifications, we expected the unit cost changes as shown in

Table 6.

Table 6 Estimated SST Topology 1 unit cost

Volumes	Cost
Up to 10 units	£110k
10 to 50 units	£ 60k
50 units +	£ 45k

This cost estimate is based on material costs from products used during the project, improvement identified and changes in labour cost considering higher volume production.

10 Planned implementation

Considering the learnings gathered from LV Engine implementation and results of trial site, we built confidence that LV Engine solution can be effective for the growing issues that DNOs are facing in LV Networks. On that basis, we intend to follow an ambitious plan to work towards a roadmap to bring this solution to the business and have wider deployment of this unit. The roadmap that we currently considered includes the following key activities:

Activity 1 - Knowledge transfer from ERMCO (original manufacturing project partner, a US based company) to UK manufacturing party (or parties)

Activity 2 - Upgrade the design and Manufacture second generation of LV Engine

Activity 3 - Install and commission 18 LV Engine sites as planned in RIIO-ED2

Activity 4 - Fresh site selections for inclusion in RIIO-ED3 plan

Activity 1 Has been ongoing since Q4 2024, several UK based manufacturers have been contacted for potential collaboration in technology knowledge transfer and building manufacturing capabilities in the UK. While ERMCO delivered their commitments during LV Engine project delivery, their latest business strategy does not include strong presence in the UK or Europe, therefore knowledge transfer to a UK based entity with potentially a licensing arrangement can be a desirable solution. There will be commercial discussions and agreement in details yet to be finalised. SP Energy Networks will endeavour to play its role as an end user to influence this activity for a reliable and reasonably justifiable commercial UK presence.

Activity 2 An updated technical specification of SST Topology 2 has been prepared which informs general technical requirements of generation II of this solution. The prospective UK vendor needs to value engineer some of the design aspects and also optimise the supply chain to reduce the cost of unit as much as possible for a strong commercially competitive solution. This activity should be part of knowledge transfer from ERMCO to the UK based technology inheriting company. Following the design, manufacturing and factory testing should take place. As of today, the funding arrangement for such activity is still under discussions between ERMCO, and other parties with considerations to rely on capital investors or innovation allowance fundings.

Activity 3 SP Energy Networks have 18 LV Engine sites planned as part of RIIO-ED2 delivery. We are looking to install the second generation of this solution in these 18 sites. If we successfully deliver the 18 sites in ED2, the integration of the solution in our business and prospect of further deployments will be strengthened. Nonetheless, there is a strong dependency on design and manufacturing the second generation which also dependents a UK based company inheriting the LV Engine technology.

Activity 4 Considering we make acceptable progress on Activity 1 to Activity 3, the plan is to further study and include LV Engine solution in our ED3 submission which then allow continuation of the solution deployment. We also plan to approach other DNOs for their considerations of LV Engine in their ED3 plan which can consequently derive the unit cost down and more competitive.

11 Learning dissemination

The LV Engine Project has actively and regularly shared the progress, learnings and project achievements with a wide range of stakeholders to allow for regular feedback so it can be included in project development as we progressed. We also endeavour to encourage UK manufacturing and growth UK SMEs activities in power electronic technologies by giving them the insight on grid issues and mark opportunities for power electronic technologies. Table 7 shows the list of dissemination activities carried out during LV Engine project.

Table 7 List of dissemination activities

Dissemination	Date	Target Audiences
Project Progress Reports	Annually (2018 to 2023)	Regulatory, DNOs, Academics, manufacturers
Energy Innovation Summit	Annually (2018 to 2024)	DNOs, Academics, Manufacturers and Consultants
Internal dissemination	Regularly with various stakeholder to raise awareness, training and achievements	Senior Management, Design engineers, Operation engineers
Project progress videos published on project website	2018, 2023, 2024	DNOs, Academics, Manufacturers and Consultants
Presentation in collaboration with UK Power Networks and CSA Catapult	2019	to Power electronics community and SMEs
IEEE Webinar	2020	DNOs, Academics, Manufacturers and Consultants
DNO workshop	2019	DNOs
LV Engine workshop PowerTech conference	2019	Academics
SPEN Utility of the Future conference	2019	City Council, SPEN customers, Academics, Consultants
DSO workshop	2019	DNOs
CIRED	2019, 2020,	DNOs, Academics, Manufacturers and Consultants
PCIM Europe	2019	Academics, Manufacturers and Consultants

Dissemination	Date	Target Audiences
IET AC/DC conference	2020	DNOs, Academics, Manufacturers and Consultants
IEEE Journal – Transaction on Smart Grid	2021	Academics, Manufacturers and Consultants
IEEE General Meeting	2022	Academics, Manufacturers and Consultants
IET AC/DC conference	2021, 2022	DNOs, Academics, Manufacturers and Consultants
CIRED Working Group – DC Distribution Networks	2019-2021	DNOs, Academics, Manufacturers and Consultants
ENA Working Group - Testing methodologies for power electronic devices	2021	DNOs, Academics, Manufacturers and Consultants
COP26 – GLASGOW	2021	World Senior Leaders, Innovators
Cenex	2022	EV charging infrastructure manufacturers, innovators
IET Power Electronics, Drive and Machine	2022, 2023	Academics, Manufacturers and Consultants
IET Powering Net Zero	2023	DNOs, Academics, Manufacturers and Consultants
eGrid2023	2023	DNOs, Academics, Manufacturers and Consultants
Cigre Webinar	2023	DNOs, Academics, Manufacturers and Consultants

Project was also recognised for its achievements by winning the Gold IET Excellence and Innovation Award in 2023. In addition, LV Engine was shortlisted for Utility Week award in Innovation category.

Figure 45 LV Engine won Gold IET Excellence and Innovation Award

12 Key Project learning documents

The following documents contain the key learning information.

LV Engine Deliverable #1 - Technical specification of SST and functional specification of the LV Engine schemes' including relevant control algorithms.

This document provides the technical and functional specifications of LV Engine power electronic solutions. This covers both hardware and control strategy requirements. We used this document at the procurement stage for appointing Reading this document should be in conjunction with learning generated from implementation

LV Engine Deliverable #2 - Detailed technical design of SST by the manufacturer and life cycle assessment. (Part 1, Part 2)

This deliverable has two parts: Part 1 Provides the technical design and simulation studies carried out for LV Engine products. The design document shows the rational and engineering background of using different solutions or power electronic topologies. Part 2 provides a method used for life cycle assessment of the LV Engine product and its environmental impact compared with other solutions.

LV Engine Deliverable #3 - Manufacture SSTs for LV Engine schemes.

This document provides learnings from manufacturing the power electronic technologies and the installation carried out for LV Engine schemes.

LV Engine Deliverable #4 - Complete network integration tests.

In order to de-risk the LV Engine live trial schemes, we carried out a pre-trial laboratory testing mimicking LV Engine schemes but with actual equipment deployed in LV Engine substation. This document provides the methodology and results of tests carried out.

LV Engine Deliverable #5 - Establish the system architecture of LV Engine schemes.

LV Engine solution IT integration, architecture design and testing carried out to establish end to end communication.

LV Engine Deliverable #6 - Demonstrate the functionalities of SST.

This document provides the live trial results in various LV Engine schemes and also tests carried out on three LV Engine trial sites.

LV Engine Deliverable #7 - Best operational practices of SSTs.

This report uses the learnings from trial sites to provide technical guidance on use cases, applications and cost benefit analysis of the LV Engine solution in comparison to conventional reinforcements or distribution transformer fitted with onload tap changer.

LV Engine Deliverable #8 - Identify a trial site for replicating LV Engine solution within UK Power Networks.

This report reflects the collaborative works carried out between UK Power Networks and SP Energy Networks to identify potential LV Engine solutions within UK Power Networks distribution network.

LV DC switchgear technical and functional specifications

This document provides the technical and functional specification of the LVDC switchboard that was deployed in LV Engine LVDC trial site. We used this document as part of tendering materials for appointing the LVDC switchboard manufacturer.

LVDC protection strategy

This document provides a summary of protection strategy that was used in LV Engine LVDC scheme site.

LV Circuit Breaker Controllable Devices Technical and functional specifications

This document provides the technical and functional specification of the controllable LV circuit breaker that was purchased through a tendering process in LV Engine.

LV Engine Progress Report 2018 - Progress and learning captured during 2018.

LV Engine Progress Report 2019 - Progress and learning captured during 2019.

LV Engine Progress Report 2020 - Progress and learning captured during 2020.

LV Engine Progress Report 2021 - Progress and learning captured during 2021.

LV Engine Progress Report 2022 - Progress and learning captured during 2022.

LV Engine Progress Report 2023 - Progress and learning captured during 2023.

13 Data access details

To access and download material generated through the project, please visit the LV Engine website using the below link:

LV Engine - SP Energy Networks

Access to the project data must be requested by contacting SPInnovation@spenergynetworks.com.

Please provide the following information in your request:

- Affiliation
- Position
- Contact details of requesting party
- Relevant project and type of data required
- Reasons for requesting this data and evidence that this data will be used in the interest of the UK network electricity customers

Full details on the SPEN data sharing policy is described on the link below: https://www.spenergynetworks.co.uk/pages/data_sharing_policy.aspx

14 Material change information

We initially plan to complete the project by December 2022 in line with Project Direction. However, due to very unexpected COVID 19 pandemics, we faced number of significant challenges in supply chain and resources availabilities that delayed the project. This was in addition to challenges we naturally had for a uniquely innovative development.

In order to complete LV Engine deliverables and achieve the target learnings, we requested Ofgem for the project deadline to be extended with target for completion by 31 December 2024. This extension will be in line with NIC Governance allowing 2 years delay in project completion.

15 Contact details

Mr. Christopher Carter

Head of Innovation

SP Energy Networks, North Cheshire Trading Estate, Prenton Way,

Birkenhead, Prenton CH43 3ET

Email: spinnovation@spenergynetworks.co.uk

Registered Office:
Newington House
237 Southwark Bridge Road
London SE1 6NP

Company:
UK Power Networks
(Operations) Limited

Registered in England and Wales No: 3870728

Ali Kazerooni
Future Networks,
SP Energy Networks,
3 Prenton Way,
Prenton,
Wirral
CH43 3ET

30 May 2025

Dear Ali,

LV Engine Close-Down Report – DNO Peer Review

Further to your request for UK Power Networks to review the Close-Down Report produced in respect of SP Energy Networks LV Engine NIC funded project, I can confirm that we have undertaken this review and consider that the objectives and deliverables as agreed in the Project Direction have been satisfied by SP Energy Networks.

In addition, we can confirm that we consider that the Close-Down Report to be clear and understandable and contains sufficient detail and information to enable a DNO, not closely involved with the project, to make use of the learning generated to implement their own network solution as part of a Business as Usual offering.

Should you wish to discuss anything further or have any additional requirements that you need to address in respect of the LV Engine project, please do not hesitate to contact me.

Yours sincerely

Andrew Burton
Innovation Project Lead
UK Power Networks

ARUP

7th Floor
1 West Regent Street
Glasgow
G2 1RW
United Kingdom

t +44 141 332 8534

arup.com

22 July 2025

Ali Kazerooni
Future Networks
SP Energy Networks
3 Prenton Way
Prenton
Wirral
CH43 3ET

Dear Ali,

LV Engine 3rd Party Verification

Paragraph 8.82 of the NIC Governance Document requires that at "the end of a Project, the Funding Licensee must commission a report from an independent third party that verifies whether the Project Deliverables have been achieved.

The third party must:

(i) have sufficient levels of expertise and knowledge to enable it to verify that the Project Deliverables have been achieved and, if not, the reasons for this; and

(ii) not be affiliated with the Network Licensee or its Project Partners.

Where a Project Deliverable has not been achieved the report must explain why and whether the Network Licensee is responsible for this."

Arup's role is that of the independent third party, not affiliated with SPEN or its Project partners. We have used our professional knowledge and expertise to verify the Deliverables of the LV Engine Project have been achieved based on the evidence provided.

The LV Engine project has produced nine deliverables which will support the future efficient connection of LCTs.

1. Technical specification of SST and functional specification of the LV Engine schemes' including relevant control algorithms.
2. Detailed technical design of SST by the manufacturer and life cycle assessment.
3. Manufacture SSTs for LV Engine schemes.
4. Complete network integration tests.
5. Establish the system architecture of LV Engine schemes
6. Demonstrate the functionalities of SST.
7. Best operational practices of SSTs.

Ove Arup & Partners Limited | Registered in England & Wales
Registered Number: 1312453 | Registered Address: 8 Fitzroy Street, London, W1T 4BJ

8. Identify a trial site for replicating LV Engine solution within UK Power Networks.
9. Comply with knowledge transfer requirements of the Governance Document.

Arup's review confirms that Deliverables 1 – 8 were achieved at a level that meets expectations and Deliverable 9 is on track to exceed expectations pending publication of the Close Down Report.

Your sincerely,

Stephanie Hay
Associate Director

d +44 141 202 7634
e stephanie.hay@arup.com